Structural Roof Systems for Athletic Stadia

By

Bartley J. Miller

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ABSTRACT

Stadiums are the great stages upon which legends are made, and from which spectators receive excitement and inspiration. As such interesting and important structures, stadiums not only facilitate grand spectacles, but also enhance them through powerful architecture and innovative engineering. In recent years, structural designers have been pressed to develop the most functional, structurally inventive and architecturally celebrated sporting venues. The technological evolution of modern stadiums during this period may be most effectively traced through advances in the design of their structural roof systems.

This study investigates the major design concepts, issues and implementations of various stadium roof configurations through structural descriptions, an assessment of advantages and disadvantages of each system, and individual case studies. Because of their distinctive characteristics that transcend conventional materials and design techniques, air-supported, cable-supported and retractable roof systems will be discussed. A number of recently developed design innovations that pose unique solutions but have not yet become common practice in the construction of athletic stadiums will also be included. Collectively, they symbolize progress in stadium design and the speed with which roof systems have evolved.

Thesis Supervisor: Jerome J. Connor, Jr.
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Stadiums provide the backdrop to memories of past glories and hopes for future triumphs. Spectators attend live sporting events to be part of those joyous occasions, to experien the atmosphere surrounding the contest, and to witness the greatness of their heroes (figure 1.1). They carry with them the heightened anticipation of spectacle and excitement. As the great stages upon which legends are made and from which fans derive such inspiration, the stadiums themselves must not only facilitate such grand delights, but should also enhance them. In combining an importance that is, to some, a passion, with stringent functional requirements and monumental scale, the design of a stadium should encompass powerful civic architecture and inventive engineering. Stadiums are an extremely interesting and exciting building form.

Figure 1.1: A capacity crowd of spectators enjoys the experience of a live sporting event

Sports stadiums and arenas accommodate not only sporting events, but also concerts, trade shows and conventions, effectively influencing a broad spectrum of society. They are as much a part of our culture as our office buildings, churches, and town halls. Stadiums have the opportunity to become social and architectural landmarks that enrich the identity of a city and create significant economic benefits and cultural prestige. They also regularly attract that city's largest assemblies of people. As such important structures, stadiums should be designed with both form and function in mind.

1.1 Stadium Design History

The design of stadiums has a long history. Greek "hippodromes," originally designed as U-shaped arenas built to accommodate foot and chariot races, have held sporting events since the 8^{th} century B.C. The Romans were building vast stadiums over 2,000 years ago, and their amphitheatres took on a more enduring form: an elliptical arena surrounded on all sides by high-rising tiers and immense seating areas. The Coliseum in Rome (82 A.D.), which held 55,000 spectators, set a standard for elegance and durability and even boasted such modern innovations as a movable roof (figure 1.2).

Figure 1.2: The Coliseum, Rome, Italy

While various cultures erected stadiums through the ages, none were fully enclosed with roof structures, and so the challenges associated with long-span roofs were never truly addressed. The birth of modern stadium design and construction, therefore, can be traced to the 1960's and is exemplified by the opening of the Houston Astrodome in 1965 (figure 1.3). The 60,000-seat Astrodome--immediately dubbed the "Eighth Wonder of the World"--was the world's first fully enclosed, all-weather, multi-purpose stadium. Its success began an extraordinary period of stadium construction in the United States and worldwide that continues today.

Figure 1.3: The Astrodome—"The Eighth Wonder of the World"

Several social and cultural factors contributed to the demand and popularity of stadiums in the 1960's, but the most notable was the development of television and the broadcast of live sporting events to a growing worldwide audience. At a cost of $35 million, the Astrodome provided numerous amenities that attracted die-hard sports fans and new enthusiasts alike. The structure boasted cushioned seats, 53 futuristic "Skyboxes," and a splendid $2 million scoreboard featuring visual extravaganzas, animations and instructions for fans. The roof was constructed of rigid steel covered 325.000ft^2 and spanned 642 feet, twice that of any previous structure. In designing the roof, the engineers had created a structure that pushed the limits of materials and the engineering technology of the day. To make the conversion from football to baseball, 10,000 field level seats would rotate on tracks to align with either the foul lines of the baseball diamond or the sidelines of the football field. A type of artificial grass, commonly called "Astroturf," was invented to make up for the lack of sun, and was laid down for Opening

Day in 1966. When the Astrodome opened on April 9, 1965, spectators had seen nothing like it before.

1.2 Stadium Design Advances

After the success of the Astrodome, architects and engineers immediately began to explore alternative designs that could improve both the functional and aesthetic characteristics of this new breed of sporting venue. The concrete covered, 70,000-seat Seattle Kingdome and the massive 95,000-seat Louisiana Superdome (figure 1.4) soon followed in the 1970's as enclosed stadiums using conventional materials. The Kingdome was demolished in 2000, but the Superdome continues to facilitate Super Bowls, NCAA Final Fours, political conventions, concerts and also serves as the home of the NFL's New Orleans Saints. As the world's largest steel-constructed, covered space, the Superdome is an awe-inspiring site to behold. Still, many feel that the dome is outdated, and has not kept pace with the changing needs of today's sporting venues.

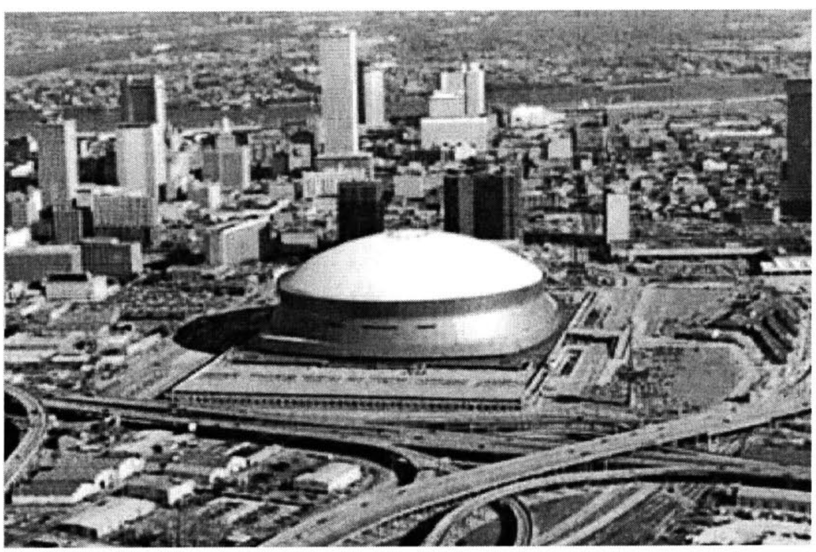


Figure 1.4: The Louisiana Superdome, New Orleans, Louisiana

Since then, they have explored the effectiveness and practicality of numerous architectural forms, materials and structural systems. As a result, designers have made many breakthroughs and produced several awe-inspiring design concepts. Modern engineering expertise allows today's stadiums to take a nearly unlimited array of spectacular forms.

Instances in both the United States and abroad show the ways in which technology can be used to create highly imaginative designs. Montreal Olympic Stadium, constructed for the 1976 Olympic Games, is an ideal example of the intermingling of form and function (figure 1.5). The stadium is an extremely futuristic and visually remarkable large-scale structure. It has been host to several notable events in addition to the Games, including professional sports, rock concerts and trade shows. The 575' tower, finally completed in 1986, is the highest leaning structure in the world and is crowned by a two-story restaurant and observatory. The fabric roof was originally designed to be retractable, but remains closed today due to technical difficulties and high costs.

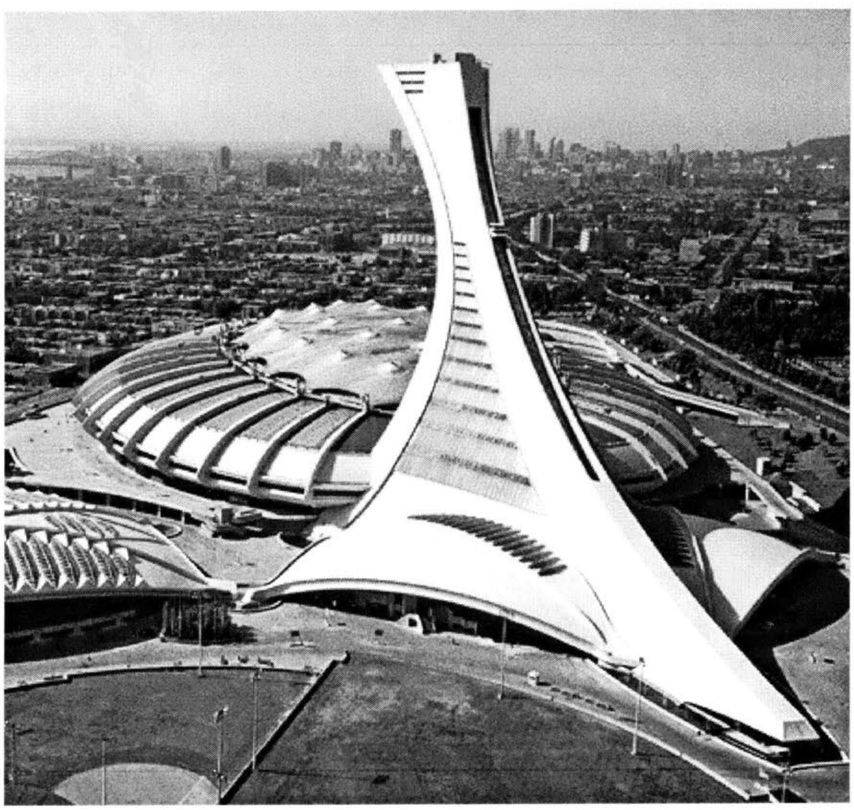


Figure 1.5: Montreal Olympic Stadium, Montreal, Canada

Designers have not only explored the value of alternative structural forms, but also alternative materials and structural systems. The Saddledome in Calgary, Canada showcases both a striking architectural effect and an efficient use of prestressed, post-tensioned concrete (figure 1.6). The design of the Saddledome utilizes the advantages of prestressed concrete not only in the bowl, grandstands and tiers of the stadium, but also in the roof system. Built to host the 1988 Winter Olympics, the structural form is a sphere intersected by a hyperbolic parabaloid that generates a dynamic roofline. Three hundred ninety-one, lightweight, precast concrete roof panels, supported by a grid network of tension cables, were used to form the thin-shell roof in an arrangement that provides minimum building volume and maximum unobstructed views of the playing surface. The precast roof panels provide several structural advantages, including quality assurance through off-site fabrication, ease and acceleration of erection and enhanced architectural freedom.

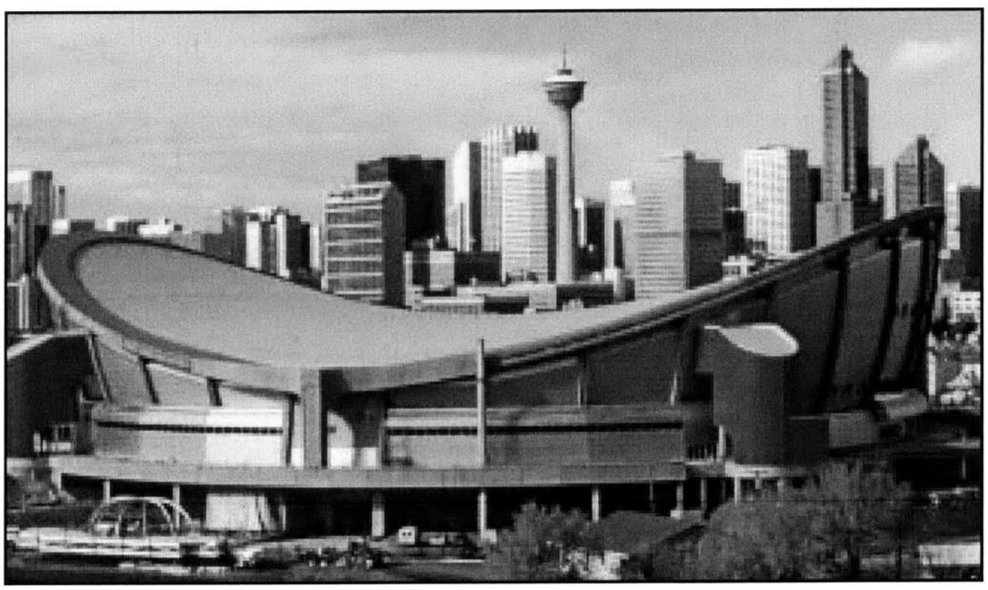


Figure 1.6: The Saddledome, Calgary, Alberta

Occasionally, a stadium can symbolize progress and facilitate a great celebration, as The Millennium Dome did in London, UK (figure 1.7). While under pressure from the media from its conception, and with the added difficulty of a tight construction timetable, the Millennium Dome showcased the technological prowess of the UK as the most intriguing element of London's much-anticipated Millennium Exhibition on January 1st, 2000. Directed by the Government appointed Millennium Commission, designers of the dome met the engineering challenge of erecting the largest enclosed space in history. Covering 860,000ft^2, the dome is a lightweight tension structure built into a spherical profile, supported by twelve compression masts. Though not technically an athletic stadium, but rather an exhibition hall, the design and construction of the Millennium Dome is widely acknowledged as a highly significant engineering achievement. Despite continued media scrutiny, the dome remains a very exciting and memorable experience.

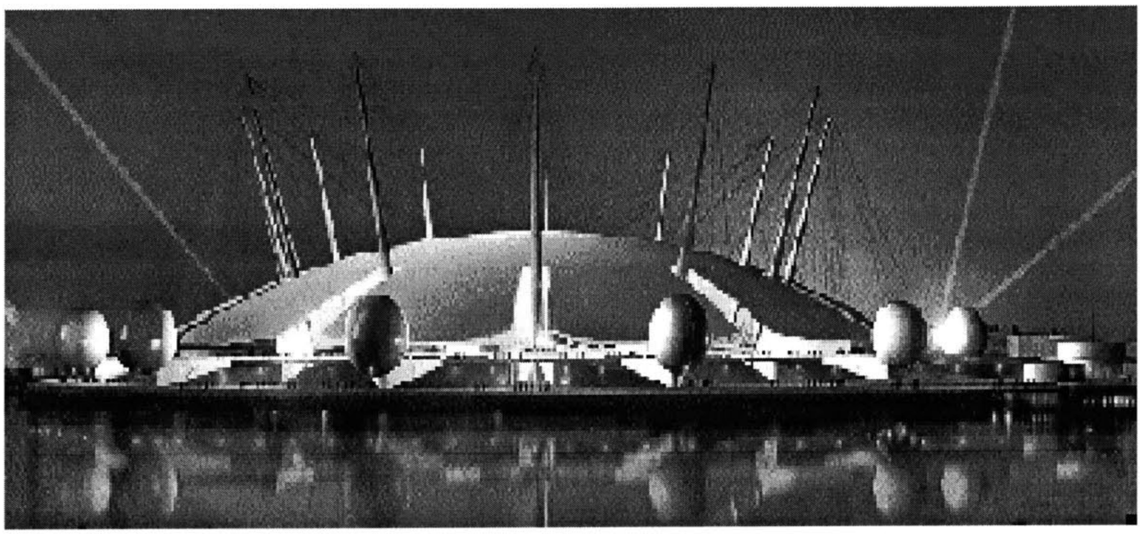


Figure 1.7: The Millennium Dome, Greenwich, UK

1.3 Stadium Design Challenges

Modern stadiums and arenas are huge financial commitments that are often wholly or partially funded by local communities. As such, it is crucial to utilize an economic design. However, both the public and the owners have high expectations of the finished product. A stadium must be architecturally expressive, functional in terms of event management, crowd comfort, sight lines and acoustics, and there also must be no question of its structural integrity or safety.

Architecturally, challenges in stadium design result from their enormous scale, inward-looking form, long periods of disuse and functional requirements. Difficulty arises from an inability to integrate such a structure successfully into an urban fabric. From an engineering standpoint, the large scale and geometric complexity of stadium structures tests the limits of materials and demands sophisticated design techniques.

The most fundamental structural design challenge in stadiums involves the extremely large clear spans required for playing fields and sight lines. For long spans, dead loads must be minimized, which causes the problems of instability under varying loads such as wind and snow. Steel trusses, which avoid bending stresses and carry loads only in axial forces, thin concrete shells, cable networks and lightweight, cable-restrained fabrics have all been widely used to create the needed balance between lightness and stiffness.

The interaction of the environment with the architectural and structural elements of a stadium also has a significant impact on a facility, effecting its design, cost and success. Leakage, for example, has been a persistent problem for many conventional, long-span roof structures. Data must also include rainfall, wind patterns, air temperature, relative humidity and turf microclimate. Wind, snow and seismic loads play an important role in the design of such large and often complicated structures. Wind and snow loads, especially, are highly sensitive to shape. However, by providing adequate information about these load types through computer modeling and wind tunnel testing, an enhanced, safer and more economical design solution can be achieved.

It is crucial to address all design loads and climatological information as early as possible in the design process. Long span roofs of any kind can be especially susceptible to wind. The roofs of stadiums become subject to vibrations and oscillations due to their shape and flexibility. These structures require a great deal of information on dynamic loads to reduce overdesign and improve safety. For facilities with retractable roofs, aerodynamic stability under various wind conditions combined with several roof positions needs to be assessed to identify unstable circumstances, while lateral loads need to be determined to assist in the design of the roof drive system.

Wind tunnel tests are commonly used to determine wind loading and its effects on stadiums. Miller Park in Milwaukee, Wisconsin, with its fan-shaped retraction and unique geometry, required a great deal of wind load studies (figure 1.8).

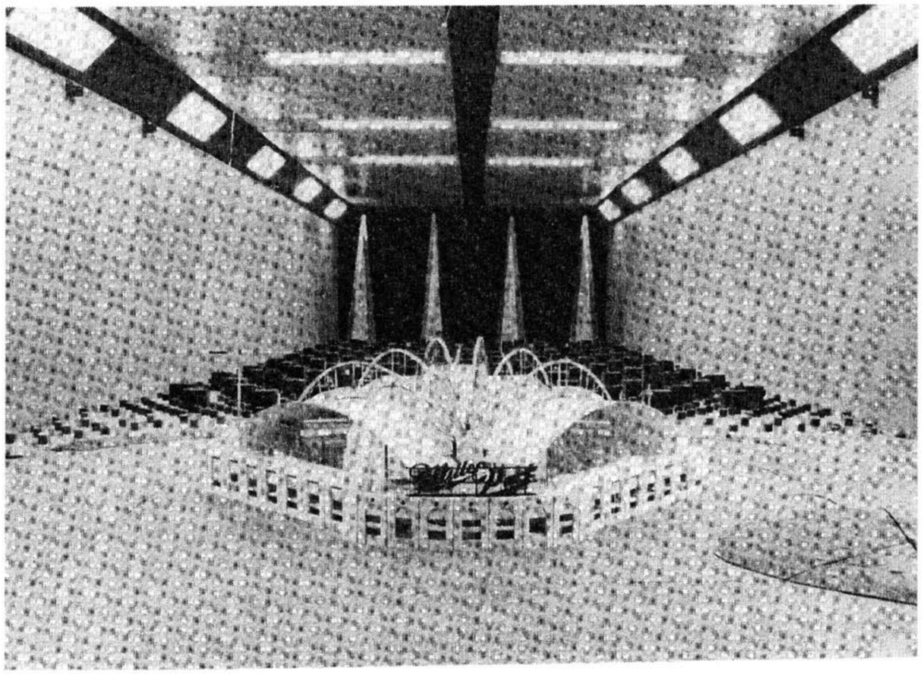


Figure 1.8: 1:400 scale aero-elastic model and wind tunnel testing of Miller Park, Milwaukee, Wisconsin

Snow loads on large roofs can be excessive and result in failure of the structural system. Unbalanced or concentrated loads resulting from snow drifting and melting are primary dangers. Accurate snow load information can identify areas where the analytical code could be exceeded or where it causes overdesign. Snow drifting in key areas such as roof joints, areas above driving mechanisms and up against the sides of roof panels can increase maintenance costs and reduce safety.

Because it is located in the cold, snowy midwestern climate, Miller Park's retractable roof also had to be designed with particular attention paid to snow loading and the various patterns it could take (figure 1.9).

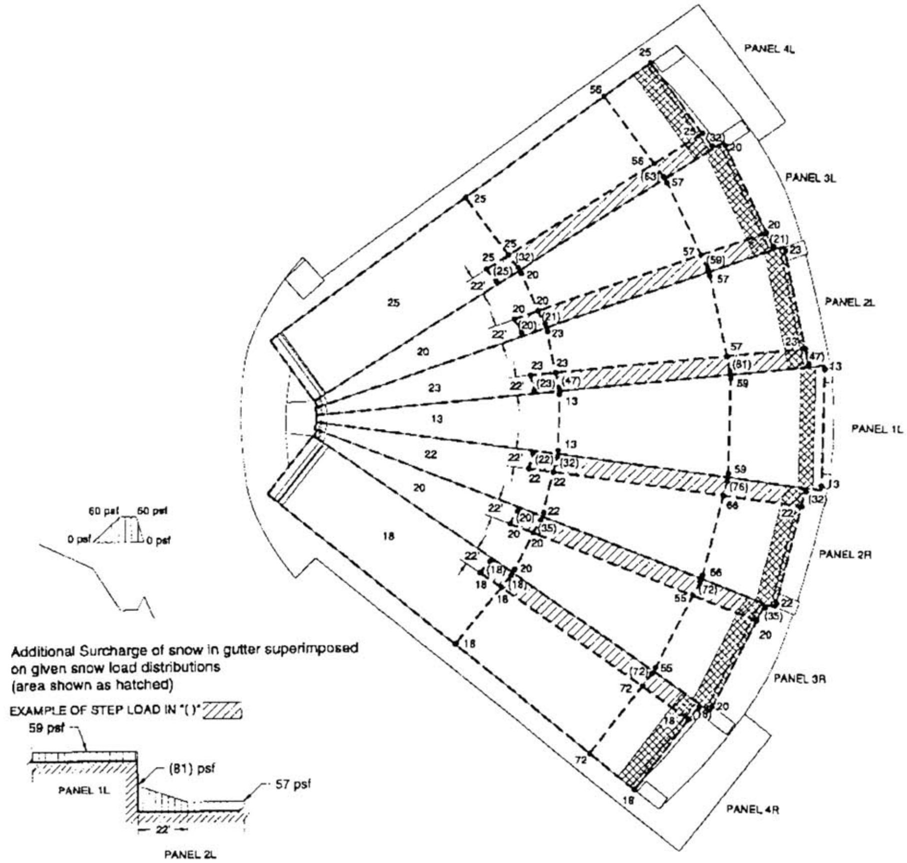


Figure 1.9: Snow loads and distribution on Miller Park retractable roof

The combination of scale model studies and computer simulation models allows for a more scientific approach to determining design loads, member sizes, and ultimately the success of the structure. For Miller Park, design issues included wind loads on the cladding, structure and drive systems, wind vibration, snow loading, spectator comfort and even the effects of wind on the baseball in flight.

An additional, truly unique design consideration in stadiums is the identification of the potential trajectory of a baseball in flight. The mechanisms by which the structure sheds wind loads can have an impact on a ball's behavior. Information about the different types and directions of hits under various wind conditions and, for retractable roofs, roof positions, can provide guidelines for optimal roof geometry and potential field configurations.

1.4 Thesis Objective

Although the Astrodome has served as the home of either the NFL's Houston Oilers or major league baseball's Houston Astros for over 30 years, the stadium and others like it have begun to show their age. A boom in stadium design and construction is now underway, and in a race to design the most functional, structurally innovative and architecturally celebrated sporting venues, engineers and architects have pushed the limits of modern structural and mechanical systems. Amid this flurry of construction activity, the design and construction industry has been forced to constantly reassess its approach to these complex projects. The technological evolution of modern stadiums from the age of the Astrodome to the present may most effectively be traced through advances in the design of their structural roof systems.

The objective of this study is to investigate the major design concepts, issues and implementations of various stadium roof configurations, including air-supported, cable-supported and retractable roofs. These roof systems were chosen for their unique design characteristics that transcend conventional materials and design techniques, and because they symbolize an evolution in stadium design and construction. Several other more recently developed design innovations that pose unique solutions but have not yet become common practice in the construction of athletic stadiums will also be discussed. Many of these structural systems, either currently or at the time of their construction, represent the latest in cutting-edge, technological progress. Collectively, they demonstrate the speed with which stadium design has advanced.

2. Air-supported Roof Structures

In the 1970's, engineers began to develop new methods for handling live loads and reducing dead loads in long span, stadium roof structures. Air-supported roof systems, often called domes, were the first breakthrough in long-span technology and provided an interesting design solution. The first large-scale, low profile, cable-restrained structure was designed by David Geiger, then a professor at Columbia University, and built in Osaka, Japan in 1970 (figure 2.1). The dome covered an area 262' by 462' at a construction cost of $2.6 million. The low cost, aesthetic quality of the translucent space and the confirmation of the design theory led the extension of the air-supported system to other applications and even larger spans. There are currently six major air-supported structures in the world, and numerous smaller examples.

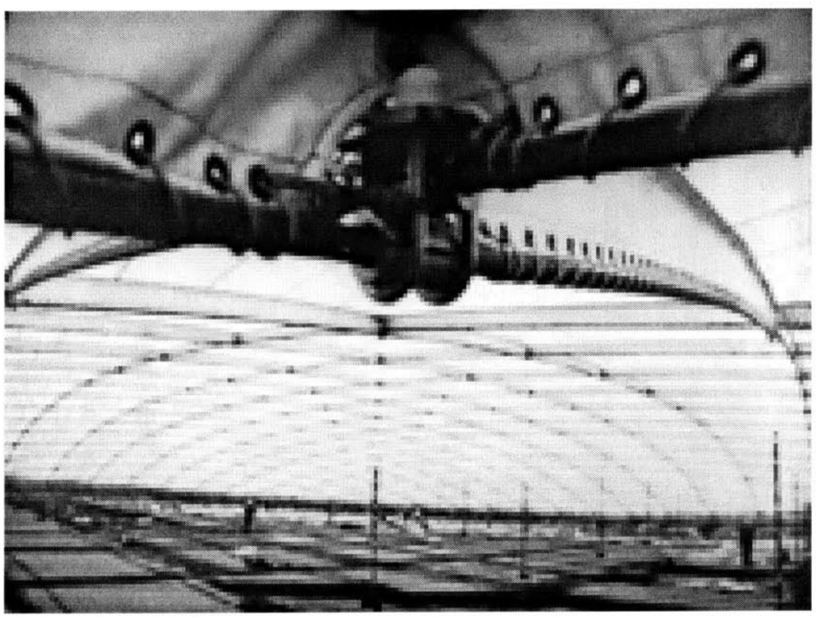


Figure 2.1: The United States Pavilion, Osaka, Japan

2.1 Structural System

Air-supported structures are, as their name suggests, held up by air pressure. This unique method of structural support provides wide-span, column-free, interior space ideal for athletic stadiums. Air-supported structures have four essential elements: pressurization systems, a fabric membrane covering, special access, and anchorage. A system of fans holds up the fully enclosed structure by boosting air pressure at around 4.5 psi, which supports and stabilizes the lightweight fabric roof. The lightweight materials greatly reduce dead loads, which is fundamental to increasing spans. The roof is restrained, rather than supported, by anchor cables that also stiffen the fabric against flutter under uneven wind conditions. The fabric is attached to the cables in panels creating a hybrid membrane, which transfers stresses from the fabric to the cables and then on to a compression ring that resists uplifting forces. While the concept of pressurization may sound uncomfortable, the pressure differential is no greater than that of normal barometric fluctuations.

Structural efficiency in air-supported roofs depends on the principle of skewed symmetry, which requires that the cable directions be parallel to the diagonals of the superscribed rectangle. This ensures that the ring segments to which the cable ends are anchored may, for a given load, be designed for zero moment or for a minimum moment. Several shapes and configurations are possible and have been implemented (figure 2.2).

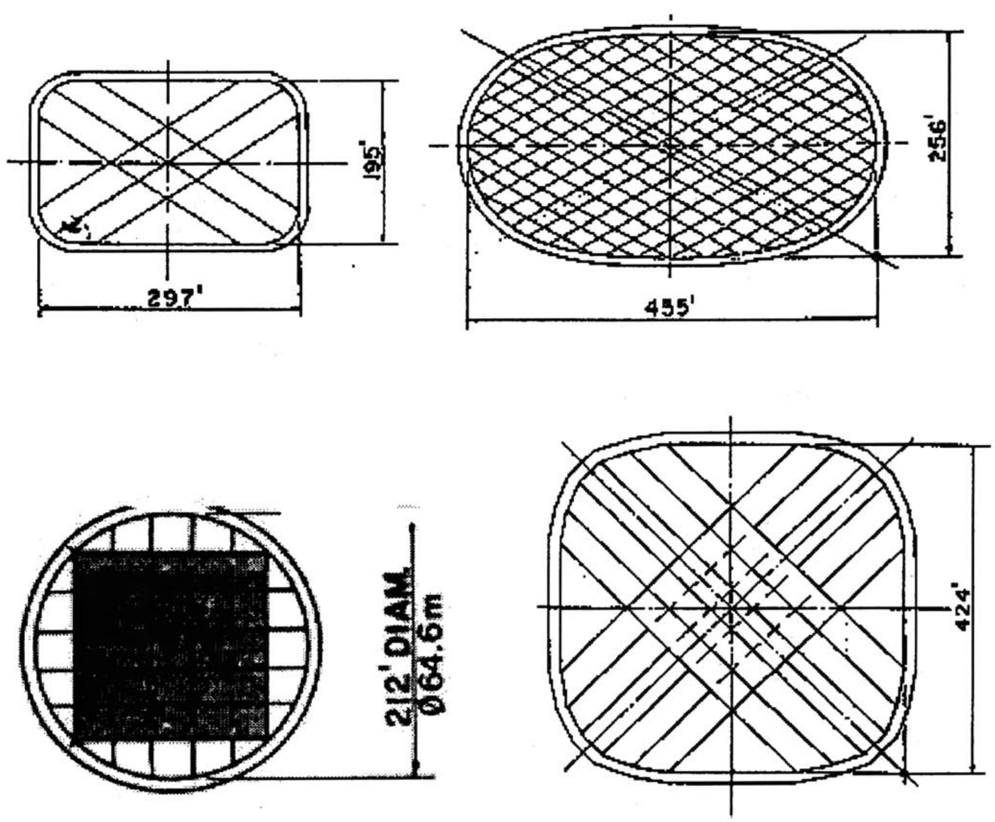


Figure 2.2: Some geometric plans for air-supported structures.

The most basic shape is a low-profile oval with a diagonal cable pattern and a funicular compression ring. Two-way cable systems and rectangular shapes with modified corners ensure that the compression ring carries virtually no bending moments. Consideration of fabric design and shipping often limit cable spacing to a maximum of 45'. Due to fabrication and the cost of connections, the minimum cable spacing accepted as economically efficient is 35' on center.

2.2 Fabric Membrane Covering

Almost all permanent fabric roofs for both air-supported and cable-supported structures in existence today are entirely synthetic. The most common fibers used for membranes are fiberglass or polyester. Fiberglass is strong and durable but deteriorates when exposed to excessive moisture; polyester degrades when exposed to sunlight. As a result, silicon rubber and Teflon are usually used as a surface coating. The solar and thermal properties of the combined fabric make it very energy efficient. The translucency of the fabric can be varied between 6% and 13%, allowing for daytime lighting to be reduced or eliminated. The Teflon has a reflectivity of up to 70%, which is advantageous in hot climates. In colder climates, additional layers can be used to insulate by creating dead air space.

The fabric is delivered in prefabricated sheets of varying shapes and lengths and are lapped together on-site. Two panels are heat welded to a Teflon film, and the resulting joint is stronger than the original fabric, and completely air and watertight. Often two layers of fabric are used for thermal and/or acoustic reasons.

2.3 Design Advantages

The air-supported scheme offers several advantages. Clearly, at approximately one pound per square foot, the fabric dome is very lightweight, which leads to the potential for longer spans and freedom from various design restrictions of other roof systems. Air-supported dome costs also compare favorably to those of other design concepts—on average one-third the cost of conventional materials like steel or concrete. Because the fabric panels are so lightweight and easily handled, savings result from lower construction and supporting structure costs, a reduced construction schedule, and an overall economy of design. The low mass of the roof also permits the construction of air-supported domes in the most severe seismic zones. The infusion of natural light through the translucent canopy adds to an appealing architectural element, creating a sense of light and space not present in conventional roof systems. Aesthetically, the design is very elegant and dramatic.

2.4 Design Disadvantages

There are also disadvantages to maintaining the shape and stability of air-supported domes. Success of the structure ultimately depends on accurate pressurization monitoring and adjustment, and, in some cases, snow load management. Many factors contribute to the challenges of keeping pressures constant, including mechanical failures, internal and external temperatures, wind speeds, humidity, and crowd behavior and comfort. Wind loads, for example, create an uplift force and pressure decrease in the dome. High volumes of spectators entering or exiting at one time may decrease pressure rapidly. Maintenance of an air-supported structure is critical, and must be meticulously performed for the life of the structure.

Excessive snow also causes a need for added pressure to support the extra weight and, in many cases, must be melted. Snow loads up to 12lb/ft^2 can normally be carried by increasing the internal pressure, but beyond this greater air-pressure becomes impractical when considering the design of doors and exit velocities. In the event of failure of the snow melting or pressurization system, the roof slowly deflates and hangs freely in the deflated position.

In the majority of cases, deflations of air-supported structures do not constitute a critical failure of the structure, since the roof will hang up over the spectator area even when in a fully deflated position. This condition occurred in the Silverdome in Pontiac, Michigan during a heavy snowstorm in 1985. However, a 1986 incident involving the deflation of the Metrodome in Minneapolis, Minnesota led to a partial evacuation of the stadium during a Minnesota Twins professional baseball game. When wind shear hit one side of the roof, the pressurization control system registered it as a surge in the building's air pressure and proceeded to dump air to compensate, rather than stabilizing the roof against the wind. The result was swaying lights and ceiling-hung speakers, fabric tears, heavy leakage and spectator panic. While it took only nine minutes to stabilize the roof structure and resume play, such occurrences present a major disadvantage to the air-supported roof design.

2.5 Construction Issues

The construction of air-supported structures is relatively easy. The fabric roof covering is prefabricated and transported and handled in rolls. The rolls are 30-40' wide and up to 200' long. The fabric is clamped along its edges to the cables of the cable net. In cases where the fabric must be folded to meet the stadium geometry, the fabricator must handle the fabric with care so that no tears or damage will occur. When all connections have been made, the roof is inflated into its final position.

2.6 Case Studies

The Silverdome, Pontiac, Michigan, 1975

The Silverdome is an 80,000-seat, multi-purpose stadium designed primarily for football, but can also accommodate baseball, basketball and other large assemblies (figure 2.3). Completed in 1975, the construction cost of the stadium was $55.7 million. The roof itself consists of 100, 0.30" thick, Teflon-coated, fiberglass fabric supported by internal air pressure of 5.25 lbs/ft^2 and restrained by a diagonal network of steel cables. The membrane is six-percent translucent, allowing some internal illumination.

Figure 2.3: The Silverdome, Pontiac, Michigan

The Silverdome's air-supported, cable-restrained Fiberglass fabric dome is the largest of its type in the world, covering ten acres and weighing 200 tons. It is the first successful example of a fiberglass fabric system for enclosing huge amounts of space at a comparatively low cost. The dome is restrained and shaped by a network of 18 large steel cables. A giant Sikorsky Skycrane helicopter installed the three-inch diameter cables, which vary in length from 550 to 750 feet and weigh up to 15,000 lbs. each. The dome was inflated to a height of 202 feet above the playing field by 25 large fans in about twenty minutes. Once inflated, only two or three of the fans are required to supply normal operating air pressure. The balance of the fans provides for an interchange of air as required for ventilation and as mitigation for a loss of air pressure. Other design features include alarm systems that trigger supplementary air pressure devices and a ventilation system that brings in outside air. The air-supported structure is designed to maintain its form through strenuous maintenance measures and inspections, and even with a 700 sq. ft. hole in the fabric (figure 2.4).

Figure 2.4: A guard checks the fabric roof of the Silverdome. Electric fans boost air pressure for support.

The RCA Dome, Indianapolis, Indiana, 1984

The RCA Dome, formerly known as the Hoosier Dome, provided both an economic and an aesthetic boost for downtown Indianapolis when it opened in 1984 (figure 2.5). Built by the city as a much-needed expansion to an existing convention center, the dome carried a $66 million construction cost. In addition to hosting the Indianapolis Colts of the NFL, the versatile dome is also booked year round for other events including trade shows, national and international conventions, concerts and other various sporting events. The RCA Dome can accommodate 61,000 fans in normal seating, luxury boxes, club lounges and newly renovated "super suites."

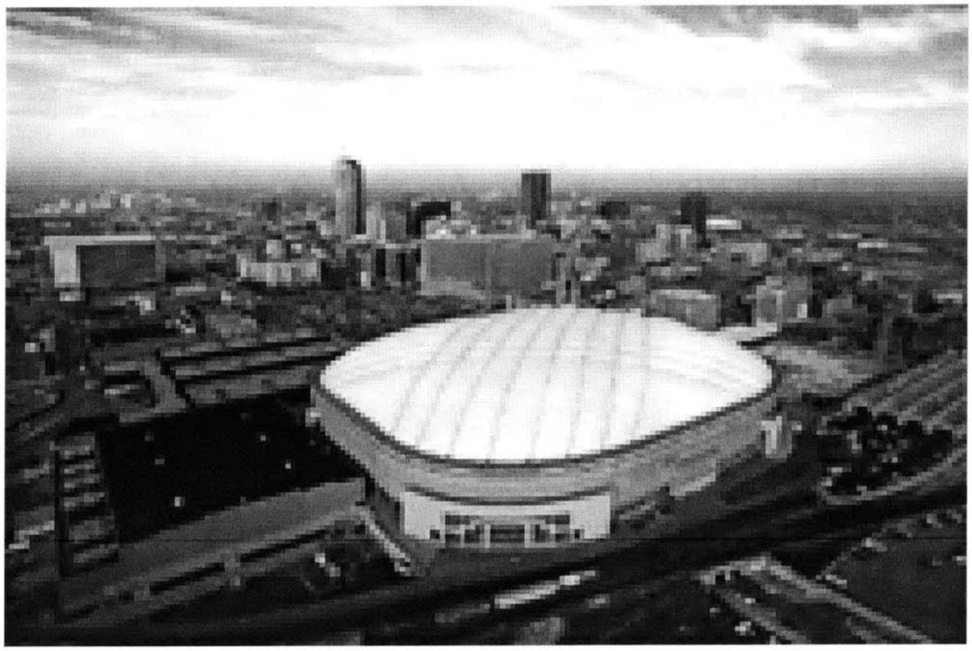


Figure 2.5: The RCA Dome, Indianapolis, Indiana

The stadium covers two city blocks and over 400,000ft^2, and the surface area of the roof is over eight acres. The roof weighs 257 tons and is supported by twenty 100-horsepower fans, though only four are normally needed at any one time. The stadium height is 193 feet, but fluctuates up to five feet under varying wind and weather conditions. Gauges monitor wind speeds on two sides, roof height, air-pressure, temperature and humidity. The dome also utilizes an eight-zone snow-melting system. The roof consists of 81 panels that are 1/32"-thick Teflon-coated fiberglass on the outside and a canvas-like material on the inside. The fabric is restrained by 16 steel roof cables averaging 660' in length.

3. Cable-supported Structures

Because of the number of deflations due to fabric tears and to the dependence of air-supported structures upon mechanical control systems and their operators, the use of these structures have become less common. As a favorable alternative, cable-supported domes often provide the lightweight and cost-effective characteristics of air-supported roofs, but do not depend on favorable weather and skilled maintenance crews for their stability

In the 1980's, air-supported roof structures evolved into cable-supported, or "tensegrity," systems. The tensegrity system was originally developed by R. Buckminster Fuller in 1954 as a "discontinuous set of compressive components interacting with a continuous set of tensile components to define a stable volume in space." Unfortunately, technical limitations in materials, equipment and analytical procedures restricted the use of tensegrity to small-scale structures for many years. The first major cable-supported structure was constructed in 1986 in Seoul, South Korea for the Korean Olympic Games (figure 3.1).

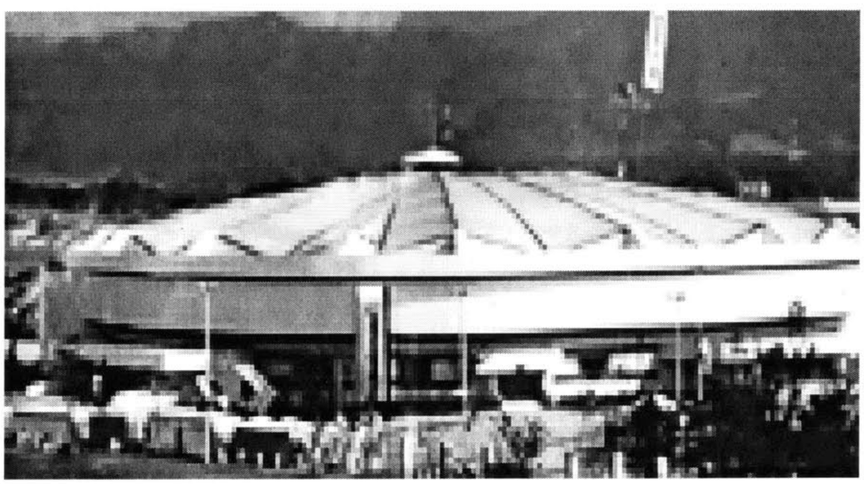
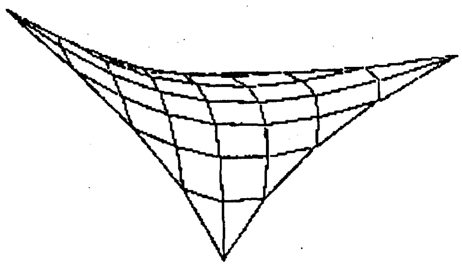


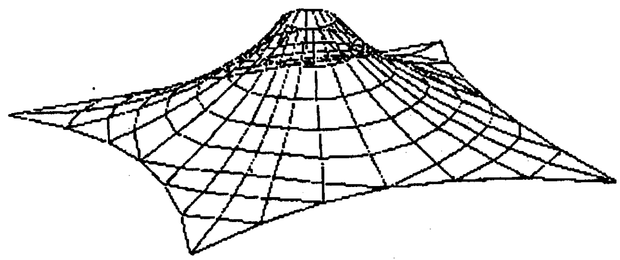
Figure 3.1: Olympic Gymnastic Stadium, Seoul, South Korea

3.1 Structural System

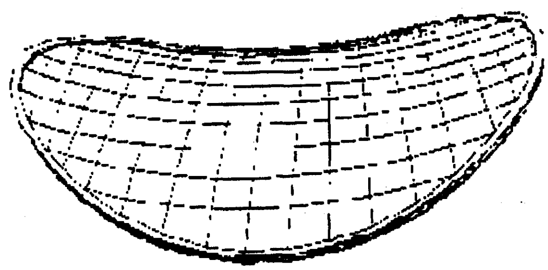
The structural system of cable-supported structures involves exploiting the properties of tensile and compressive forces, where all tensile forces are resisted by strands of cables and all compressive forces by masts or slender steel columns. The cables carry the gravity loads while stability and resistance to wind uplift is provided by the weight of the roof deck system. Due to the unlimited number of different and dynamic shapes that can be designed, these structures offer a great deal of architectural freedom and innovation, but, consequently, present unlimited analytical challenges for the engineer (figure 3.2).



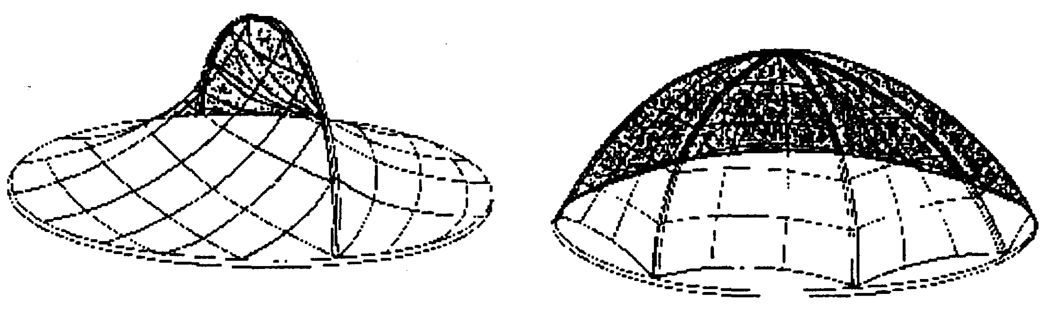
Orthogonal Anticlastic Saddle



Radial Tent



Saddle Roof



Arch-supported membranes

Figure 3.2: Some geometric configurations for cable-supported roofs

The basic types of tension structures are cable domes, mast-supported roofs, arch-supported roofs, radial tent and saddle roofs. The most common type of tension structure, the cable dome, consists of a center tension ring surrounded by a number of hoop rings also in tension, which are, in turn, surrounded at the perimeter by a compression ring.

The configuration that is most beneficial for stadium roofs is also the cable-dome. Fuller described them as structures in which islands of compression reside in a sea of tension. These structures consist of ever smaller annular rings, rigid in their vertical planes, connected to each other with cables running from the top of the larger ring to the bottom of the next, smaller ring. It can also be viewed as a radially oriented succession of discontinuous trusses in which the bottom chord is a series of hoops tying adjacent trusses together.

Cables are usually made from steel, because of its low cost, availability and long life. Kevlar and glass fiber cables are stronger and stiffer, but are more expensive and degrade when exposed to ultraviolet light. Like air-supported structures, the cover material is a Teflon coated fabric.

3.2 Design Advantages

Many of the advantages of cable-supported structures are the same as those of air-supported ones. Tension structures can economically span large distances without internal obstructions or any mechanical systems. The cable-supported domes provide the lightweight and cost-effective characteristics of air-supported roofs, but do not require such painstaking maintenance measures for their stability. Cable-supported roofs weigh approximately two to four pounds per square foot, as opposed to one pound for an air-supported roof and 30 to 40 pounds for steel frames and trusses.

3.3 Design Disadvantages

Because cable-supported roof designs are highly nonlinear due to complicated geometries and large cable deformations, the mathematics and engineering involved are very complicated. This fact, in combination with materials and a more complicated erection process, make cable-supported structures more expensive than their air-supported counterparts. Also, because cable-supported structures have a low self-weight, live loads such as snow, ice and wind represent a large percentage of the design loads and must be carefully simulated and calculated. Maintenance and inspection are also difficult. Finally, the trend toward more traditional, open-air stadiums has discouraged the design of fully enclosed, cable-supported stadium roofs.

3.4 Construction Issues

The erection of cable-supported roofs, and cable domes in particular, represent an excellent example of the interplay of design and construction. The nature of the structural system suggests that the structure needs to be intact in order to behave properly. As a result, special analyses are often required to account for intermediate construction stages.

All components are prefabricated so that they will fit together quickly when assembled on the stadium floor. The roof structure is then lifted into place as one piece using a jacking operation designed to raise the cable network and compression members slowly and simultaneously to a point where tension hoops and some additional cabling is added. The process has been compared to lifting a giant spider web by pulling on its edges (figure 3.3).

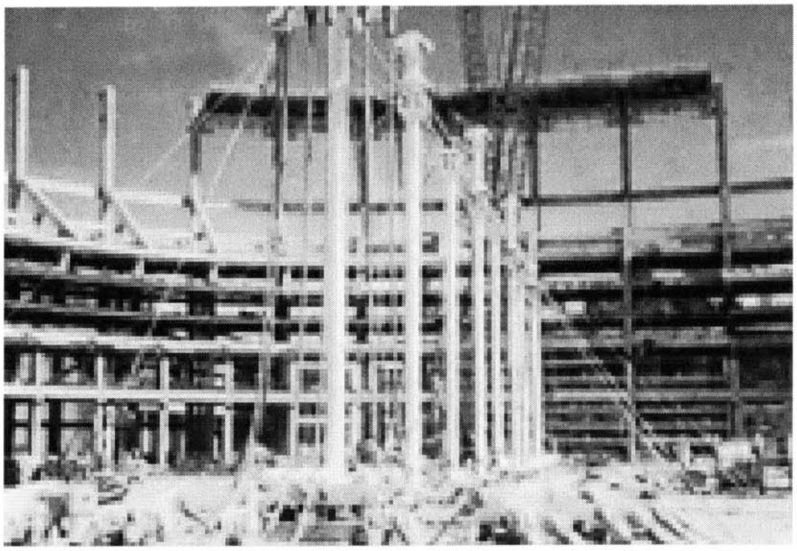


Figure 3.3: Cable system of the Georgia Dome
awaits single-assembly lift

With the assembly stabilized, the concentric hoops may be added in sequence starting with the outermost hoop. As each ring is completed, further jacking and tightening is performed. The last step is to lift the center tension ring to its final height and secure it with permanent cables.

3.5 Case Studies

The Florida Suncoast Dome, St. Petersburg, Florida, 1989

Until the completion of the Georgia Dome in 1992, the distinction of being the largest cable-supported, clear span roof in the world belonged to the Florida Suncoast Dome (figure 3.4). Erected in 1989 in downtown St. Petersburg, the 45,000-seat stadium boasts a 371,000ft^2 fabric dome that features a 6-degree tilt from the horizontal, said to emulate the trajectory of a fly ball. Though unoccupied for several years, the Suncoast Dome is now the home to Tropicana Field, and Major League Baseball's Tampa Bay Devil Rays. The stadium originally cost $138 million, but underwent a $70 million renovation in 1998.

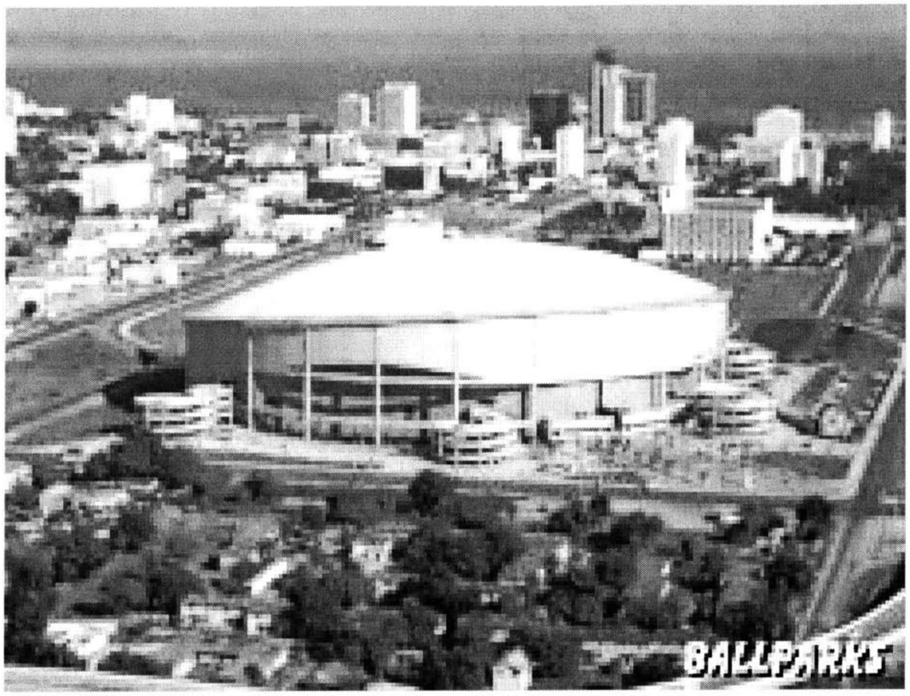


Figure 3.4: The Suncoast Dome, St. Petersburg, Florida

From the beginning, owners and engineers concurred that the stadium had to be designed as a dome to survive the sudden downpours and humidity of a central Florida summer. The roof of the dome reaches a maximum height of 225' above second base. As a "cable dome," the roof system is intended to look like an air-supported structure without the attendant problems and expenses of inflation. The design features a perimeter compression ring beam, concentric tension hoops, diagonal and ridge cables, compression struts and a center tension ring. The compression struts are arranged in concentric rings, and the bottom of each ring of struts is connected by a tension hoop. The hoops and struts are hung from the tops of the adjacent struts by diagonal cables, which are arranged radially in plan and are bundled with the ridge cables.

The Suncoast Dome has four primary hoops, with 140 0.6" diameter strands making up the largest hoop and 40 strands composing the smallest (figure 3.5). The diagonal cables vary from four to 52 strands from the inner to the outer rings. The outermost set of diagonals connects the largest tension hoop—or "D-hoop"—to the perimeter ring beam. Intermediate diagonals connect the "D-hoop" to the "C-hoop," and the system repeats itself as the elevations increase. The innermost diagonals connect the top of the "A-hoop" to the center tension ring.

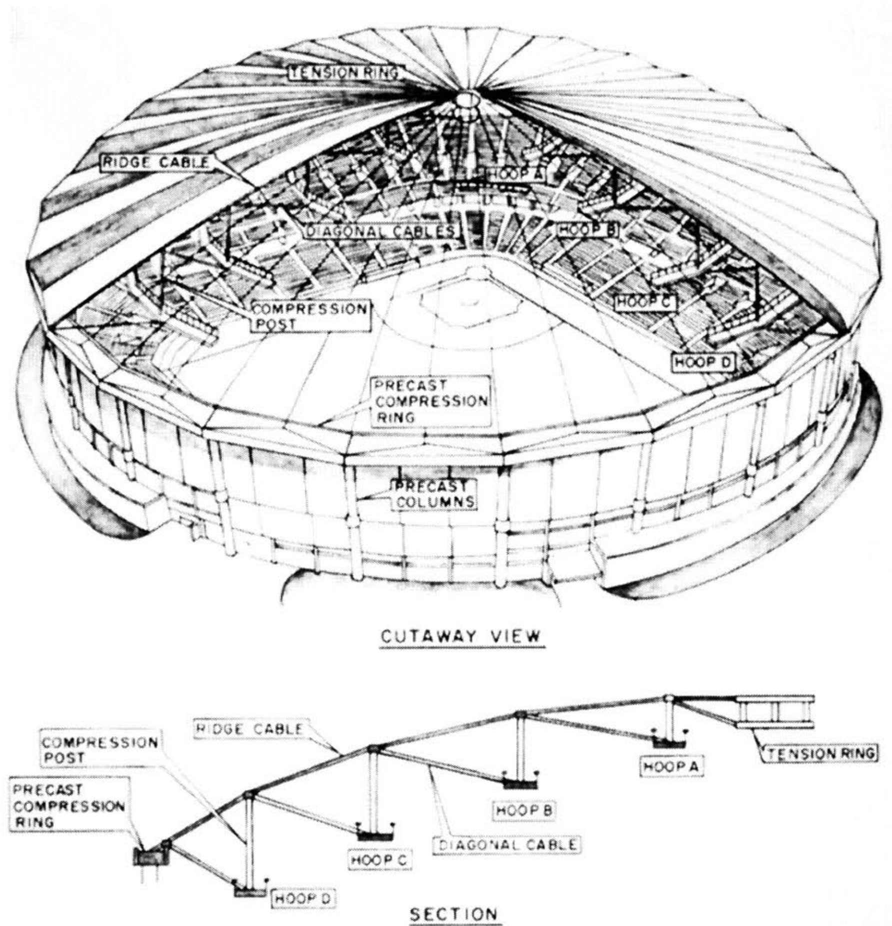


Figure 3.5: The structural system and components of the Suncoast Dome

Installation of the entire roof, including fabrication of the fabric panels, required about one year's work with a crew of about 30. Cables for the roof were rolled from multiple strands and cut to length on-site, which caused quality control problems and delays.

The Georgia Dome, Atlanta, Georgia, 1992

The Georgia Dome in Atlanta, a 70,500-seat, multi-purpose stadium capped by the world's largest cable-supported fabric roof, was completed in 1992 and marked a turning point in the application of cable roof systems (figure 3.6). Located in the heart of downtown Atlanta, the dome is the home venue for the NFL's Atlanta Falcons and the

NBA's Atlanta Hawks, was host of Super Bowl XXVIII and XXXIV, and hosted gymnastics, basketball and the finals of team handball during the 1996 Centennial Olympic Games. The construction of the Georgia Dome cost $214 million.

Covered by acres of fabric, an intricate network of cables and posts supports a 395,000ft^2, clear-span roof. The vast space has an airy feeling, with daylight diffusing through the fabric roof. When erected, the dome became an instant engineering marvel due to its vast size and apparent simplicity

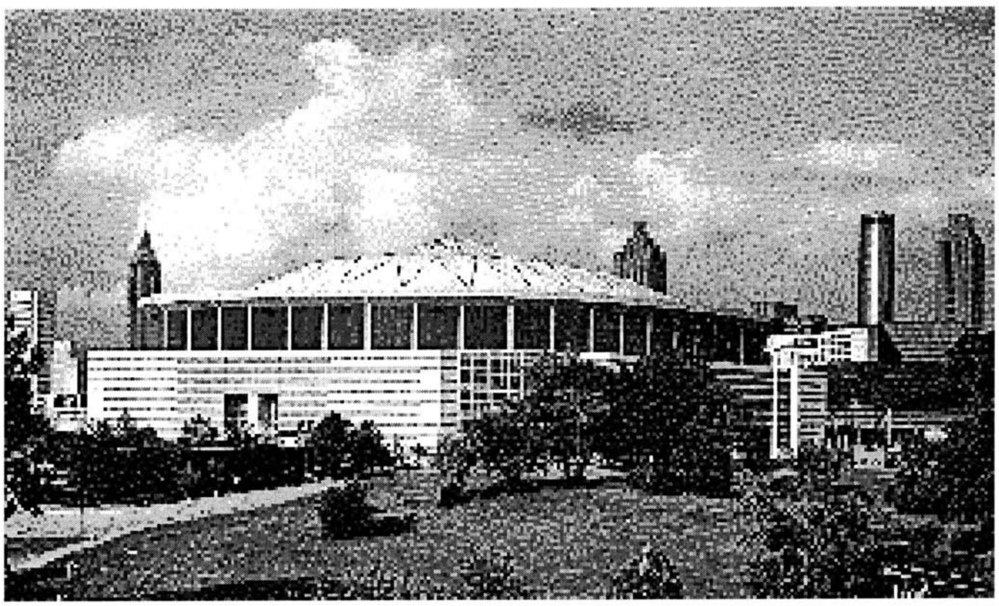


Figure 3.6: The Georgia Dome, Atlanta, Georgia

The elliptical shape of the dome made the design considerably more complicated than previous circular fabric domes because of the non-uniform stresses induced. Drawing from original theories of tensegrity pioneer Buckminster Fuller, designers developed a roof system based on triangulation and fabric panels formed from hyperbolic paraboloid shapes. Each node is braced by triangulated cables forming a continuous net. The resulting arrangement is an extremely stiff structure in which the stiffness is obtained both from the triangulation and the prestress necessary for a cable net. When viewed in plan, the dome is essentially two radial halves separated in the center by a 184' long, long-axis, tension truss.

A series of three concentric tension hoops steps inward and upward toward the crown of the dome, creating Fuller's "aspension" (ascending suspension) effect (figure 3.7). The hoops are interconnected by vertical steel posts. At the tops of the posts, which act as nodes, as many as six cables converge, secured by steel pins and welded connections.

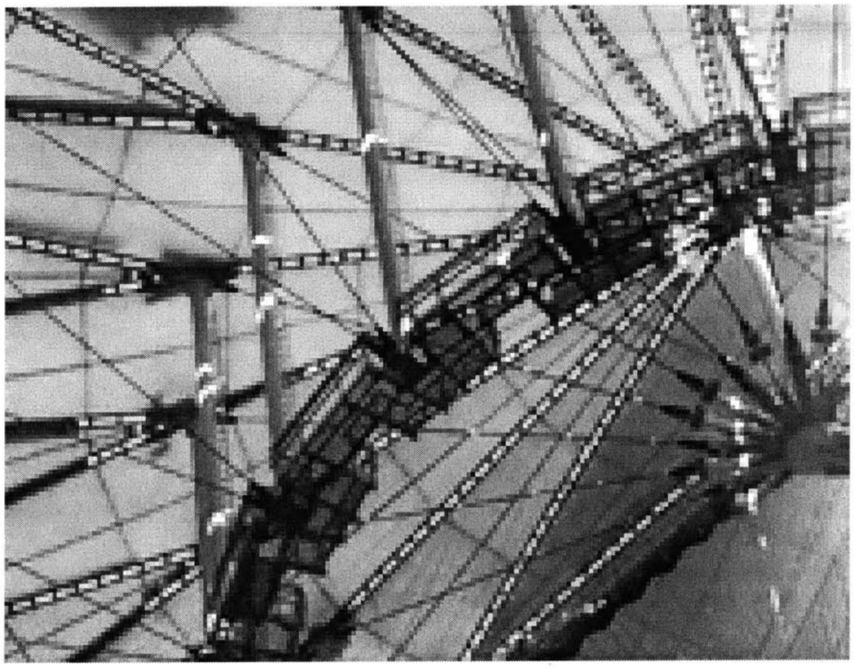


Figure 3.7: Compression ring and cable connections for cable-supported roof

The cable network is connected by embedded steel plate connections at 52 columns to a ring beam around the 2,750' circumference of the roof. The reinforced concrete ring beam, essentially a box girder that is 26' wide and 8' deep, rests on slide bearing assemblies with Teflon pads on top of concrete columns, allowing the roof to flex slightly during high winds without transferring undue stresses to the columns.

4. Retractable Roof Structures

In order to satisfy the demands of today's sports fans and franchises, a trend has developed toward the design of movable, or retractable, roof structures. In a retractable roof system, the advantages of traditional grandstand cover and fixed roof structures are combined, enabling the enjoyment of an open-air stadium while offering protection from inclement weather. Possibly more important, they allow for natural turf growth not yet fully available with a fixed roof. Natural grass helps to protect the knees, ankles and career duration of the stadium owner's most valuable investment—the athletes—in addition to giving spectators a more traditional, "old time" feel. Furthermore, the interior of stadiums with retractable roofs can be heated or cooled if needed. Retractable roofs are gaining popularity because of their versatility and increasingly manageable operation.

The first historical retractable roof was the canopy over the Coliseum in Rome. It took the form of a roll-up roof covering supported on ropes and operated by manual winches. It served more as a sunshade than a weatherproof cover because of its numerous open joints. The first modern example of a retractable roof was designed for the Pittsburgh Public Auditorium Dome in 1961 to serve as an all-seasons sports arena, exhibition hall and convention center. That roof, apart from being very expensive, suffered from mechanical problems and excessive deformations and is now permanently closed. Montreal Olympic Stadium also had several technical problems, and was completed at enormous costs. When the Toronto Skydome was completed in 1988, designers had successfully dealt with many of the structural challenges that had plagued the Pittsburgh structure, but excessive costs—estimated at over $500 million—remained a major cause of concern. Also, some believed that the engineering of the roof dominated the design of the stadium below, and that, as a result, sight lines and spectator proximity to the playing field were compromised (figure 4.1).

Figure 4.1: The Toronto Skydome, Toronto, Canada

The latest generation of retractable roof stadiums has recently begun in the United States. These roofs open completely to expose the entire stadium are to the outdoor environment. They stand apart from earlier design attempts because they rise to meet the numerous challenges associated with retractable roof systems, and effectively provide designs that are both structurally efficient and financially feasible.

4.1 Structural Systems

Retractable roofs are normally composed of rigid, steel moving panels. Panels consist of large steel trusses and are powered by large, mechanical drive systems. Retractable roofs can move in a variety of directions, including vertical, horizontal, parallel, fan-shaped revolving and central revolving. There also different types of retractions, including overlapping, stacking and folding, and roofs can be divided into any number of sections. Perhaps the most interesting retraction sequence for a movable roof belongs to Miller Park in Milwaukee, Wisconsin. The steel panels rotate around a hinge located at the front of the stadium, behind home plate. The result is a dynamic, fan-shaped retraction that opens up from center field out until all panels are stacked above seating areas along the baselines (figure 4.2).

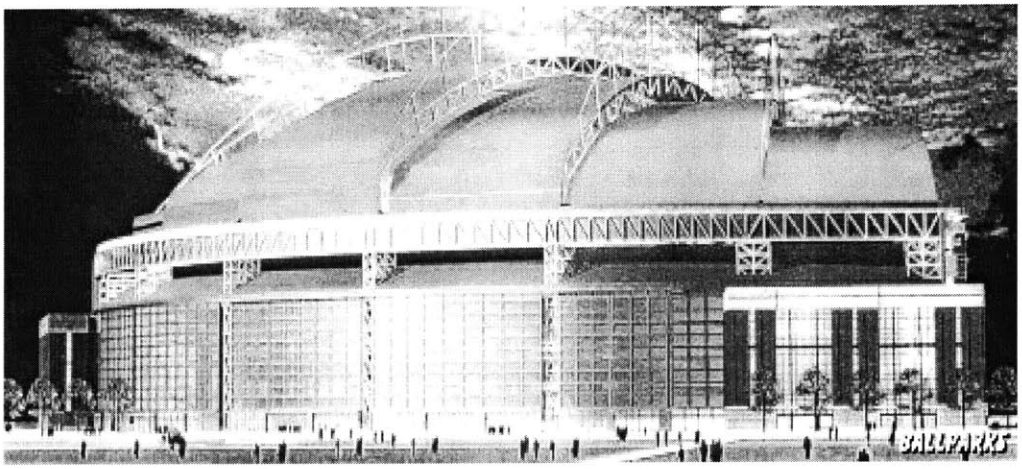


Figure 4.2: Side view of fan-shaped retractable panels of
Miller Park, Milwaukee, Wisconsin

4.2 Design Challenges

Retractable roof structures pose a number of problems not encountered in normal design of grandstands, fixed roofs or domes because of their dynamic nature. The structures are composed principally of heavy, long span cantilevers and lattice girders. The loss of structural continuity increases the weight when compared with a fully continuous arch or dome structure. Problems mainly due to the large scale of the structures include stability and rigidity of cantilevers and moving roof sections, the effect of uplift loads from wind and temperature fluctuations.

Further challenges arise from the operation of the retractable roof. Design of tracks, rollers, moving joints, locking devices and drive mechanisms must be coordinated with the various structural design concepts. Speed and frequency of retraction introduce additional technical issues, such as acceleration and deceleration rates, braking mechanisms and the resulting dynamic loads on the structure. All loads must be constantly resolved as they flow through the support structure, transporter beams, axles, wheels and rails to the substructure. Operating procedures, inspection and maintenance also require detailed study.

The structural analysis of a moving roof introduces a wide variety of load combinations that can increase the complexity of three-dimensional computer modeling immensely over a fixed roof with the same geometry. While typical stadiums may be analyzed using approximately 100 load cases, retractable roof systems may require up to 1,500. Designers of Safeco Field in Seattle, for example, were forced to devote two-thirds of the total hours spent designing an entire stadium on the roof alone. Also, because of the complicated nature of the designs and the fact that structures of this type are relatively new, there is a small number of truly experienced and qualified design firms capable of meeting these engineering challenges.

4.3 Design Keys

To address these concerns, a design must begin with close collaboration and coordination between the architect, structural engineer and mechanization consultant. The responsibilities of the mechanization consultant include advising the design team on various available technologies, costs and component testing, and often preparing designs for the mechanical systems that can be integrated into the structural design. In recent retractable roof designs, communication between specialty consultants has proven to be a key to the avoidance of problems and any resulting cost escalations.

The structural and mechanical systems in a retractable roof are interrelated, with the behavior of one having direct impacts on the other. Beyond the crucial task of identifying all load conditions, load transference mechanisms, operational parameters, dimensional consistency and rotational compatibility must also be carefully addressed to ensure a workable design relationship.

Finally, pre-construction testing of retractable roofs must be performed in order to insure a successful mechanical system. For the design of Enron Field in Houston, Texas, a prototype of the travel assembly was built and loaded with 250 tons to simulate the actual roof weight. The assembly was driven repeatedly back and forth on a 60' section of test track to simulate ten years of stadium use. The result was savings of over $500,000 in value by identifying and solving problems in the test phase before they were actually encountered on site.

4.4 Construction Issues

Integrating the design and construction process can be a huge challenge in retractable roof systems. Design decisions are often dictated by construction methods and schedules; because retractable roofs are most vulnerable during construction, erection issues and strategies must be considered during the initial roof design. The constructed position of the roof panels when they must first self-span can determine how the roof and mechanical systems relate.

Avoiding obtrusive transporter assemblies, non-standard construction methods and field welding of truss members may accelerate construction. Another key is to design each element of the stadium in a way that allows for concurrent erection of the roof panels and drive mechanisms, and the seating bowl beneath. The most successful retractable roofs to date have been able to remove the roof, from a scheduling standpoint, off of the critical path.

In some cases, retractablility can enhance or simplify roof erection. At Enron Field in Houston, for example, all of the primary steel trusses were erected on a single, fixed set of shoring towers. The mechanization system was constructed simultaneously with each truss pair, and the trusses were then rolled into position to allow for the next panel to be assembled. For Miller Park in Milwaukee, two fixed panels aligned along the baselines were erected first, and then the remaining movable panels were assembled directly above them. The completed panels provided an immediate working platform on which the steel erectors would easily access the next panel.

4.5 Case Studies

Bank One Ballpark, Phoenix, Arizona, 1998

Beginning the new trend in stadium design, the Bank One Ballpark in Phoenix, Arizona features a side-opening retractable roof and has become both a tourist attraction and a landmark for the city of Phoenix (figure 4.3). Completed in 1998 after 28 months, the 49,500-seat home of the Arizona Diamondbacks allows for natural grass and air-conditioning, and provides the opportunity to watch, play, shop, eat, drink, and even swim. The total cost of the stadium is estimated at $350 million.

Figure 4.3: Bank One Ballpark, Phoenix, Arizona

In keeping with current stadium design trends, the Bank One Ballpark was designed to be reminiscent of an "old time" ballpark. To capture the desired look, a traditional, red brick façade combines with green structural steel. Much of the steel--including the 40' cantilevered trusses--was left exposed. In addition, the structure was designed to allow for large open concourses to increase fan comfort.

The roof itself weighs 7,600 tons, reaches a 200' maximum height and covers 376,000ft^2. Because the stadium rests on a tight, 24-acre site in downtown Phoenix, the roof cannot move completely off the top of the stadium. To address the subsequent challenge of "sun shadowing" on the natural grass playing field, a telescoping and stacking structural system was developed to reduce the overall height of the structure.

The roof has eight panels—two being fixed and six able to move. Each half of the roof can move independently and is cable-driven using gantry crane technology. The six telescoping panels consist of trusses fitted with multi-wheeled bogies at each end, and can be retracted in 4 1/2 minutes, revealing a 5.3-acre opening to the sky (figure 4.4). Each panel is supported by the panel beneath it and moves on a steel wheel guide roller arrangement powered by two 200 horsepower electric motors. A computer control system adjusts the roof opening in a fashion similar to that of a camera aperture for the angle of the sun, allowing the maximum amount of light on the field and the least on the seats to reduce heat gain.

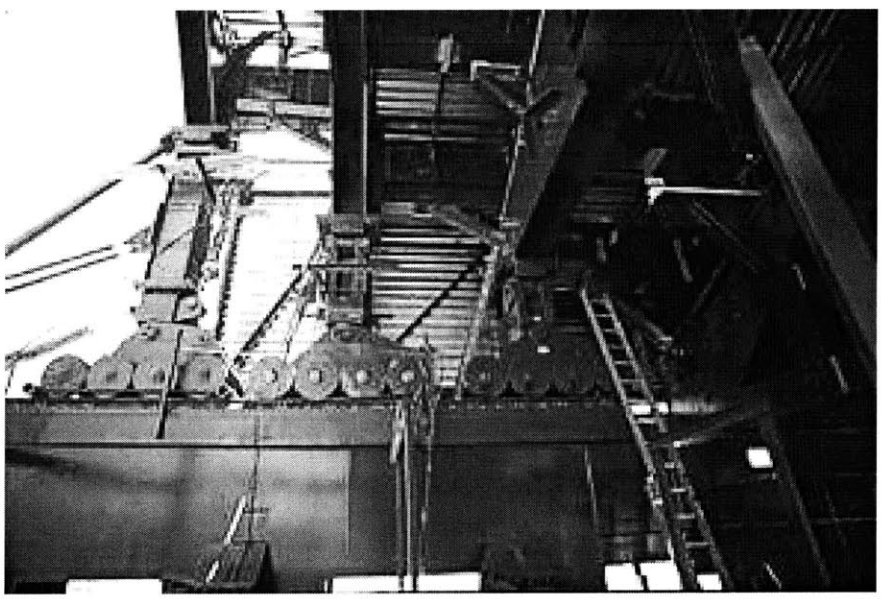


Figure 4.4: Three of the lower bogies with roof in retracted position

The moving panel system was also used as a construction aid, substantially reducing the need for temporary shoring. Fixed panels were fabricated on the ground and lifted into place, and then moving panels were erected from this elevated platform. The stadium bogie and rail systems were also used during construction to facilitate positioning and storing of panel sections.

The six, 800-ton panels are pulled by four miles of steel cable attached to two gear boxes and two 200 horsepower electric motors. To reduce the weight of the roof and its effect on the drive mechanism, high-strength steel (65ksi) was used in the roof trusses. The low roof profile also reduced the size of the drive motors required to direct the roof panels into the wind.

Safeco Field, Seattle, Washington, 1999

The rainy climate in Seattle dictates that any venue constructed to replace the outdated Seattle Kingdome should be equipped with an "umbrella" to protect fans from poor weather (figure 4.5). A retractable roof system, which can provide the traditional atmosphere of an outdoor stadium and a shield from the elements, is the ideal design solution. Safeco Field, the state-of-the-art, 47,000-seat home of the Seattle Mariners, took 27.5 months to construct and opened in 1999 at a cost of $517.6 million.

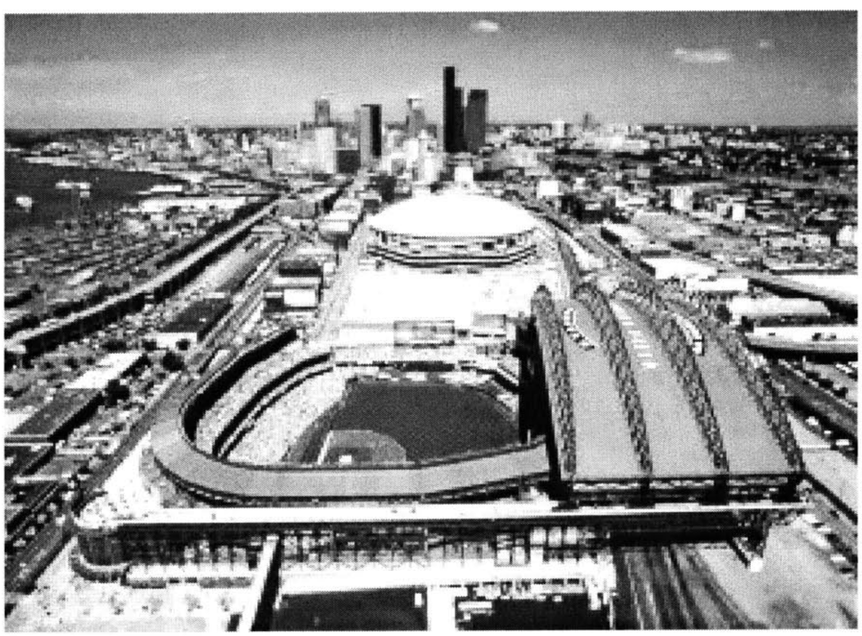


Figure 4.5: Safeco Field, Seattle, Washington

The roof of Safeco Field covers 403,000ft^2 and consists of three panels that are stacked on one side of the stadium when retracted, allowing for a larger open space than Bank One Ballpark (figure 4.6). All elements of the retractable roof are exposed steel. The roof weighs 10,800 tons, covers 8.8 acres and is supported by eight 655' long tri-chord trusses. The trusses are variable-depth, variable-width, and provide a sleek, defining architectural feature of the ballpark. The roof has a maximum height of 215'.

The three roof panels are completely independent, in contrast to those spanning Bank One Ballpark, which allowed for lighter individual panels and a simplification of the construction process. The ends of the panels are supported on large travel trucks that move along two elevated, linear runway structures on the north and south sides of the stadium. The roof moves at a rate of 1' per second, taking 10 minutes to fully open or close in moderate winds of up to 20mph.

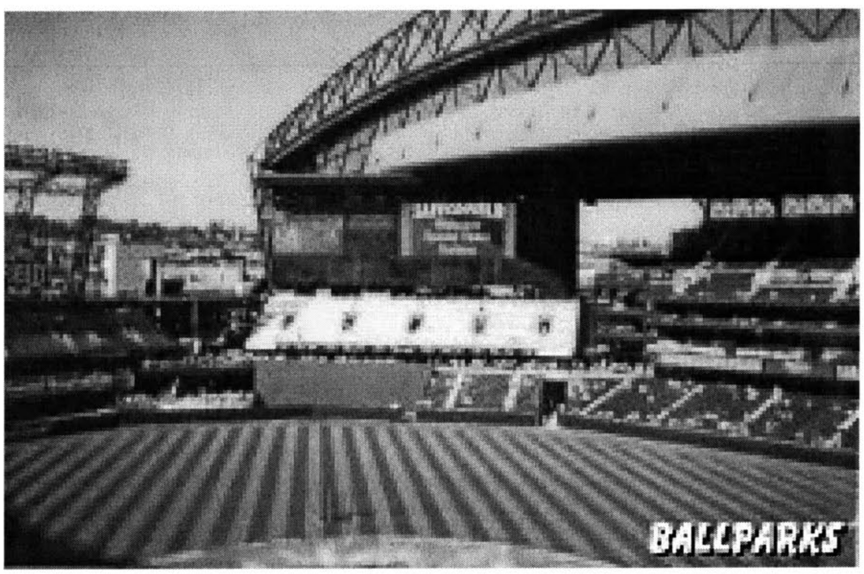


Figure 4.6: Safeco Field with roof retracted

The most interesting aspect of the Safeco Field structural design is the seismic challenge. The close proximity to the Seattle Fault required special seismic considerations, such as the design of the stadium as seven separate structures, joined only with seismic expansion joints. Also, the stadium design showcases the first-ever use of an innovative viscous damping system in the roof that reduces seismic forces by 50%. Large, three-dimensional, non-linear, time history analytical models were used to simulate different earthquakes and develop the criteria for designing the damping system. The dampers are the largest viscous dampers ever used in a building application. While rigid connections secure the roof to its lattice steel legs on the south side of the stadium, 18" diameter, 22' long dampers laterally secure the roof on the north side. The 800-kip capacity devices reduce earthquake and windstorm energy and dissipate forces from a potential seismic event. The dampers also allow the roof to deflect up to 6" through a hinge located between each horizontal truss and its leg, making the structure transparent to temperature and snow horizontal thrust force. Use of the damping devices not only diminished seismic forces considerably, but also reduced the required size and stiffness of the runways by half. Although the dampers cost $750,000 each, they ultimately created a cost savings of over $5 million.

Enron Field, Houston Texas, 2000

The hot, humid climate in Houston makes a retractable roof extremely attractive. Like in Phoenix, summer baseball for the Houston Astros would be uncomfortable, and thus less profitable, without a roof to shield spectators from the sun. The design of the retractable roof over 40,950-seat Enron Field is perhaps the most successful to date (figure 4.7). With a 27-month construction period, and at a cost of $230 million, the roof was completed faster, at a lower cost, and with less internal problems than any other modern retractable.

Figure 4.7: Enron Field, Houston, Texas

Enron Field's 280,000ft^2 retractable roof has a humpback profile, shaped by "the trajectory of a perfectly hit home run." The roof has three, structurally independent movable panels, each riding on a pair of transporter assemblies that in turn ride on a pair of rails (figure 4.8a). When retracted, the lower panels are nested below the upper panel, and when extended, the two lower panels flank the middle panel (figure 4.8b). Each box truss ranges from a 29.5' depth at its ends to 40' at midspan. To account for the projected 2' deflection of the high span, the west wall was erected to lean into the stadium. When the truss deflects, the wall is pushed out into the proper position.

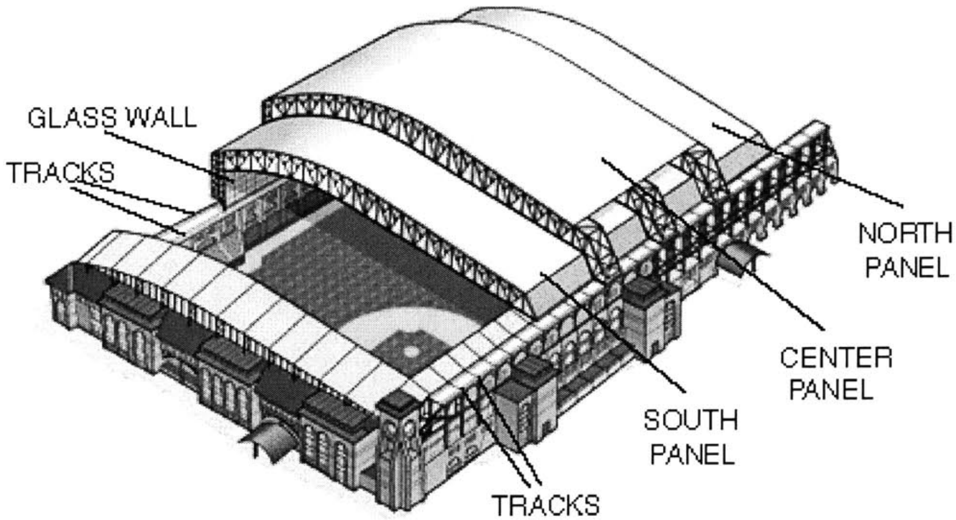


Figure 4.8a: Elements of retractable roof system

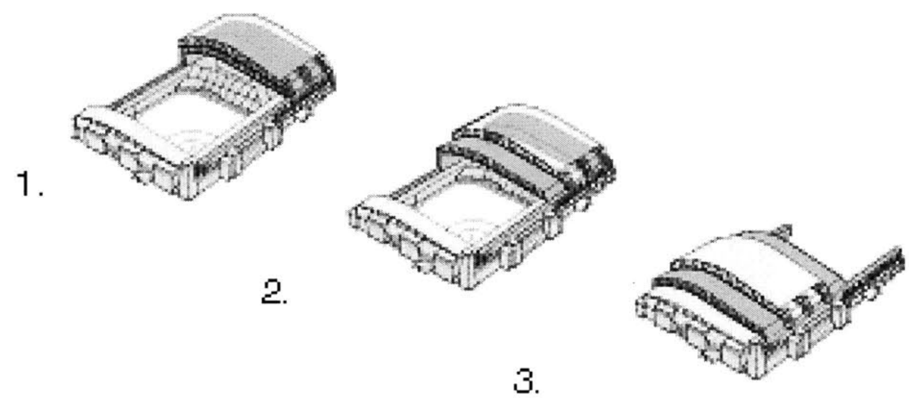


Figure 4.8b: Retraction sequence for Enron Field

The travel mechanism distributes roof loads through independent wheel assemblies rather than bogies. The purpose of that design was to avoid transferring large point loads from the roof assemblies, which contain 6,610 tons of steel, to their support structures below. The resulting, equally distributed roof loads transferred to the supports allows for a conventional framing and shallower foundations.

Forged steel wheels measuring 36" in diameter transport the three roof panels. Each of the 140 panel wheels has a braking mechanism, and 60 are equipped with 7.5 horsepower electric motors (figure 4.9). The polyurethar suspension pad acts as a spring and is attached above each wheel to distribute the roof's weight.

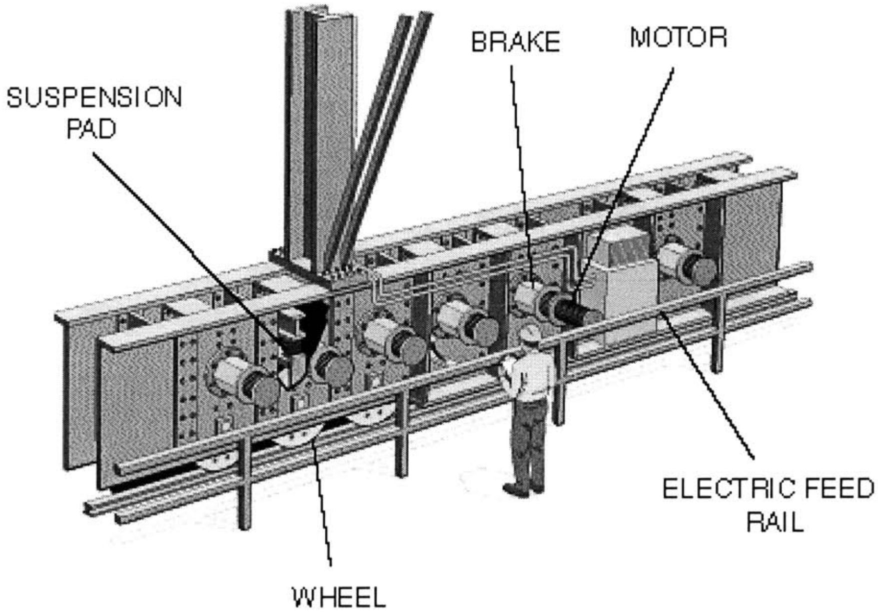


Figure 4.9: Drive mechanism for panel movement

The roof is designed to open and close in about 12 minutes during low wind conditions and within 20 minutes when subject to peak winds. When closed due to inclement weather, the roof is designed to withstand hurricane conditions of sustained winds of 72mph with peak three-second gusts of up to 110mph--the equivalent of a 100-year storm event.

Figure 4.10: Outdoor feel of Enron Field with roof retracted

5. Innovations in Stadium Design

Just as air-supported and cable-supported stadium roofs were once cutting edge technology, modern day retractable roof systems are currently considered state-of-the-art. It is exciting to imagine what the next trend in stadium design will bring. Research is ongoing in the areas of long-span structures and stadium design. The following alternatives provide a number of potential design alternatives, but have not yet become common practice in engineering or construction.

5.1 Deployable Structures

Deployable structures can be transformed, with the addition of an external energy input, from a closed or compact configuration to a predetermined, expanded form in which they are stable and can carry loads. Because of their potential for innovative applications, deployable structures offer several advantages—adaptability, mobility, and an unmistakable architectural impact, to name a few—when compared to conventional structural elements.

The development of deployable structures began in the aerospace industry, with the use of long deployable booms to stabilize early spacecraft. Other uses for these structures are found in portable shelters, solar arrays and spacecraft antennas. However, a wide variety of deployable structures have been produced in recent years. Deployable structures have many exciting potential structural applications, and perhaps the most promising is their use in retractable roofs for sports stadiums.

The principle structural elements in deployable structures are "scissor-type" or "sliding" connections, where each member of the framework has at least three nodes: one at each end connected to end nodes of other members through a hinge, and one at an intermediate point connected to the intermediate node of another member by a pivoting connection (figure 5.1). The location of intermediate node(s) and the shape of the individual members depend on the desired geometry of the structure.

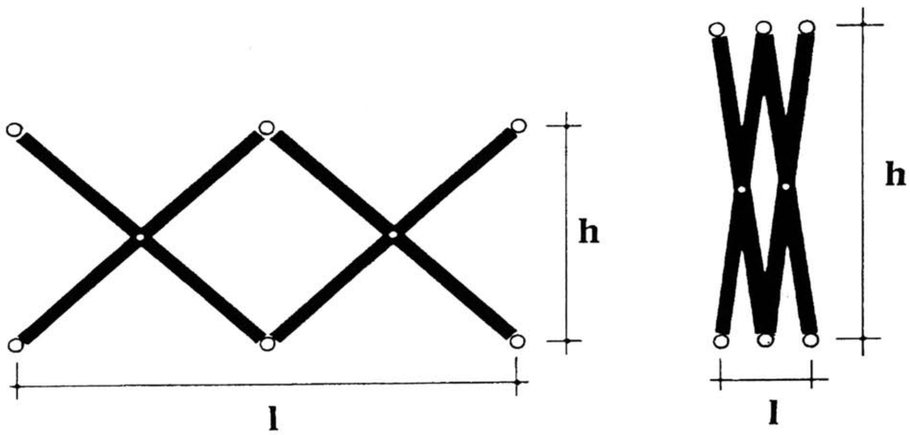


Figure 5.1: Basic scissor-type connection

Research is ongoing at the University of Cambridge to study the effectiveness of deployable structures in retractable roofs. These retractable frames are based on a special, two-dimensional tiling of parallelograms and multiple-node elements. It is possible to design structures of any shape, most commonly circular or elliptical configurations, consisting of multi-angulated rods connected by "scissor" hinges at the kink positions (figure 5.2). Although these structures contain many hinges, they retain only a single internal degree of mobility. Their motion is similar to the operation of the diaphragm in a camera lens. In the fully open configuration, all rods overlap along the outer edge.

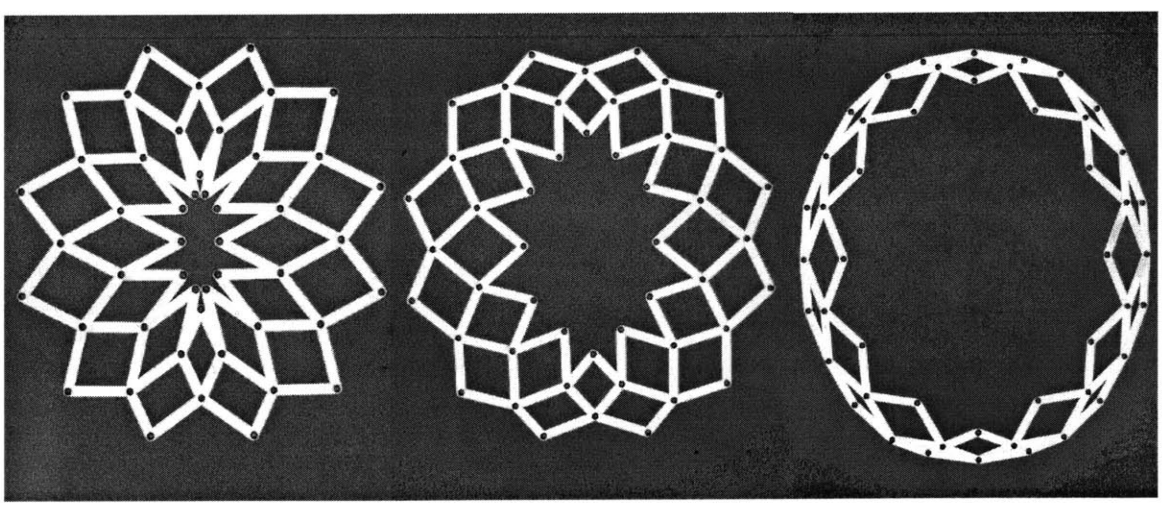


Figure 5.2: Theoretical retraction sequence for stadium roofs using deployable structures technology

These two-dimensional solutions can be extended to curved structures, such as the arched geometry of many athletic stadiums, by projecting any two-dimensional solution onto a surface with that required shape. Thus, each individual member becomes curved out of plane; however, all connectors between rods are perpendicular to the plane of projection. With this technique, double layer structures can be built, and bracing elements can be added between the upper and lower cords, to increase the stiffness of the structure.

Detailed research of practical engineering issues is currently being performed to formulate a systematic preliminary and final design methodology. This research will determine the reliability and viability of deployable structures to large-scale structural applications. Some challenges facing engineers include complicated and detailed geometric design constraints, highly nonlinear behavior during deployment and under loads, the sophisticated finite element analysis required, complex sliding connections and erection issues. Movable connections, locking devices and deployment mechanisms may also be very expensive.

5.2 Reciprocal Frame Structures

The reciprocal frame concept involves a unique three-dimensional beam grillage structural system, where all the beams both support and are supported "reciprocally" by each other (figure 5.3). The plan view of the beams is similar in appearance to the lines forming the iris of a camera shutter. Its versatility in form and consistency in strength could make it a competitive design for sports stadiums.

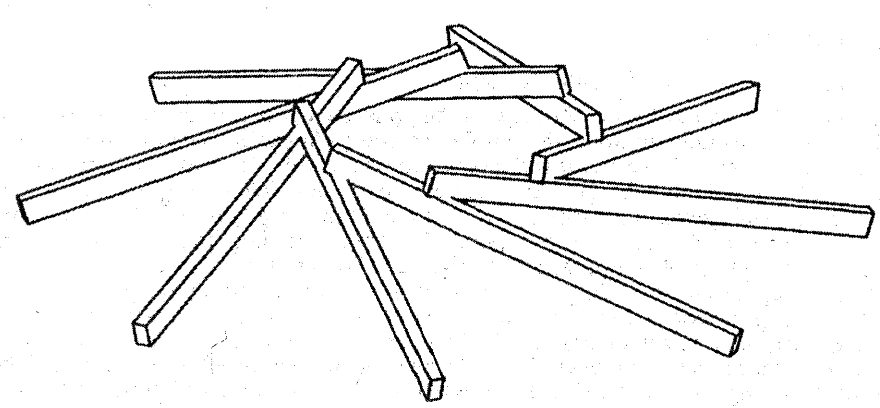


Figure 5.3: Three-dimensional view of reciprocal frame

Architecturally, the reciprocal frame system has a considerable visual effect, especially when viewed from the inside. The primary beam structure seems to be rotating about an axis, in empty space, at the center of the roof. Similar to the deployable structures concept, the roof opens from the center out, rather than from side to side, which contributes to the unique, dynamic feel of the structure (figure 5.4).

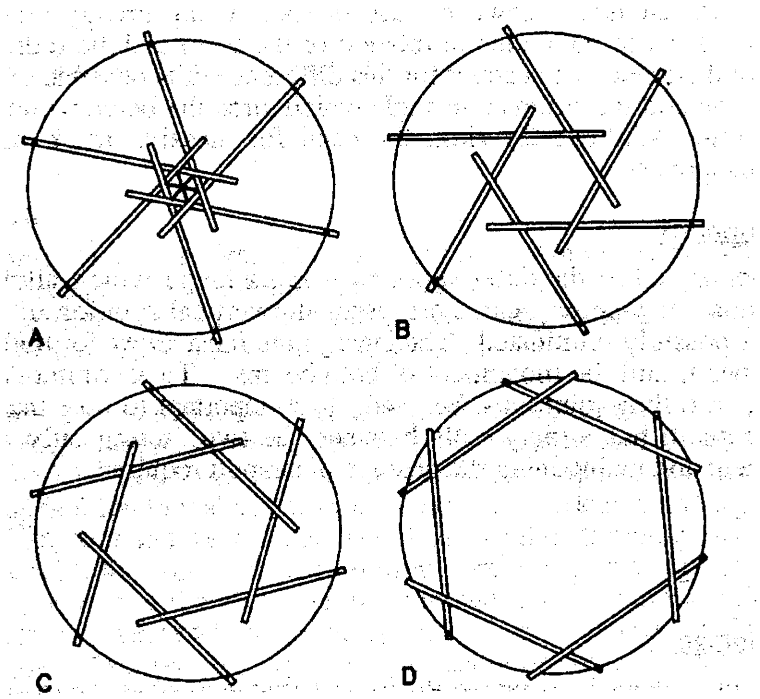


Figure 5.4: Retraction of reciprocal frame structure

During the retraction process, each beam rotates individually about its external support. The beams are connected to the outer supports using a hinge that allows for vertical and horizontal rotations. If the beams are the same length, they should all rotate simultaneously and by the same amount. The beams can rotate independently using synchronized motors or can be connected by an outer ring that is mechanically rotated, in turn rotating each beam the desired amount. Opening the roof moves the inner support of the beams along a curved path towards the outer support. The inner joints must allow for both continual support of the adjacent beam and the movement of both beams. Thus a rolling joint must be designed that does not connect rigidly to either beam but simply rolls between the two. The rollers act only as guides for the retracting movement and maintain the position of support required (figure 5.5).

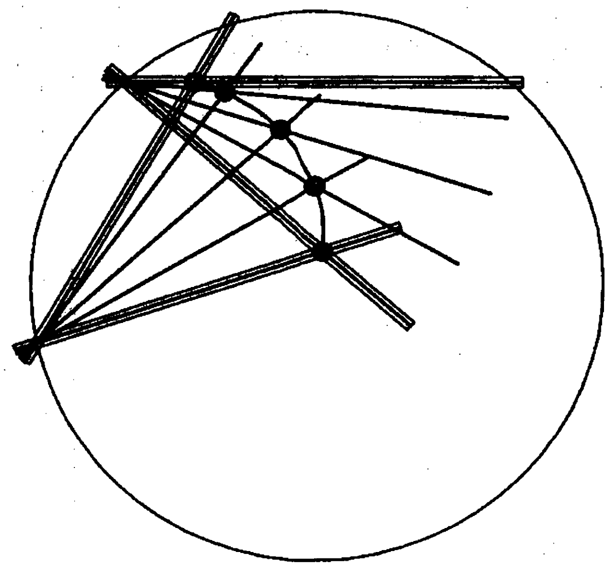


Figure 5.5: Curved path of intersection points of beams

There are several design advantages to the reciprocal roof concept. Because of the unique load distribution, there is no need for internal supports making it ideal for athletic stadiums. The system is also adaptable to a variety of materials and shapes. The 'beams' discussed can be steel, concrete or truss members. Both the inner and outer polygon can be of any shape to suit the function of the structure (figure 5.6). The reciprocal frame also allows for flexibility in choosing the cladding material, though a foldable, fabric membrane would provide a solution with the least geometrical obstacles.

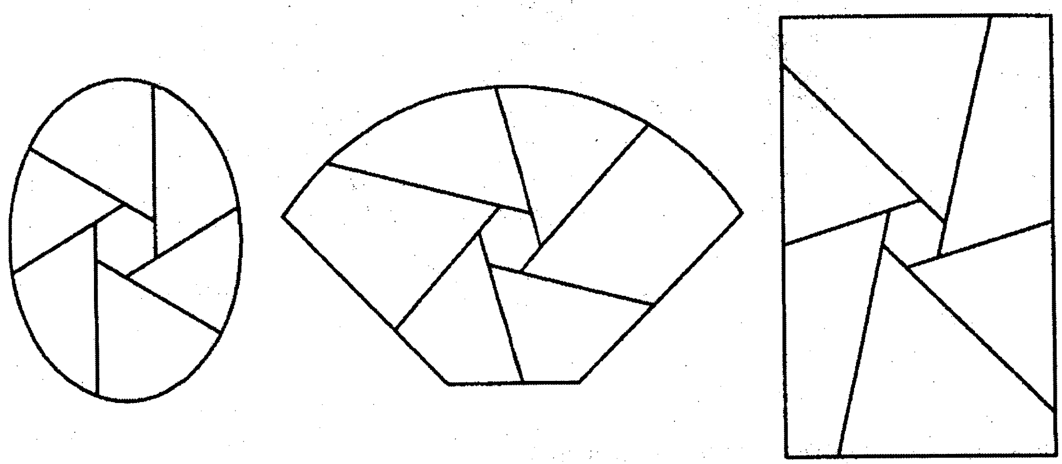


Figure 5.6: Reciprocal frame structure in various plan shapes

Further considerations include constructability issues and disproportionate collapse. Each of these potential problems is a result of the principle that each beam depends on all of the others for support. During construction, questions arise as to which beam is erected first, and how it will be supported. Also, how will the damage or removal of one beam affect the entire structure?

Because the reciprocal frame is a relatively new concept, it has not been used in a stadium design. Several specific details—such as roofing materials, drainage and joint details, and constructability--have not been completely addressed. One major obstacle may be the hole in the center of the roof that will be formed even in the closed position, since the panels can only completely close theoretically if they have no thickness. Another consideration is disproportionate collapse. As each beam depends of all of the others for its support, the removal of or damage to any one beam may result in the collapse of the whole structure. Before the reciprocal frame concept can become a viable design solution for athletic stadiums, many of these challenges must be met.

5.3 Tensegrity--Retractable Roof Option

As previously discussed, cable networks rigidized using tensegrity concepts can be adapted to a wide variety of configurations. A cable-supported retractable dome offers yet another approach based on the principle that a cable structure will remain in place over the opening in the roof, but that it will appear virtually invisible and totally transparent (figure 5.7).

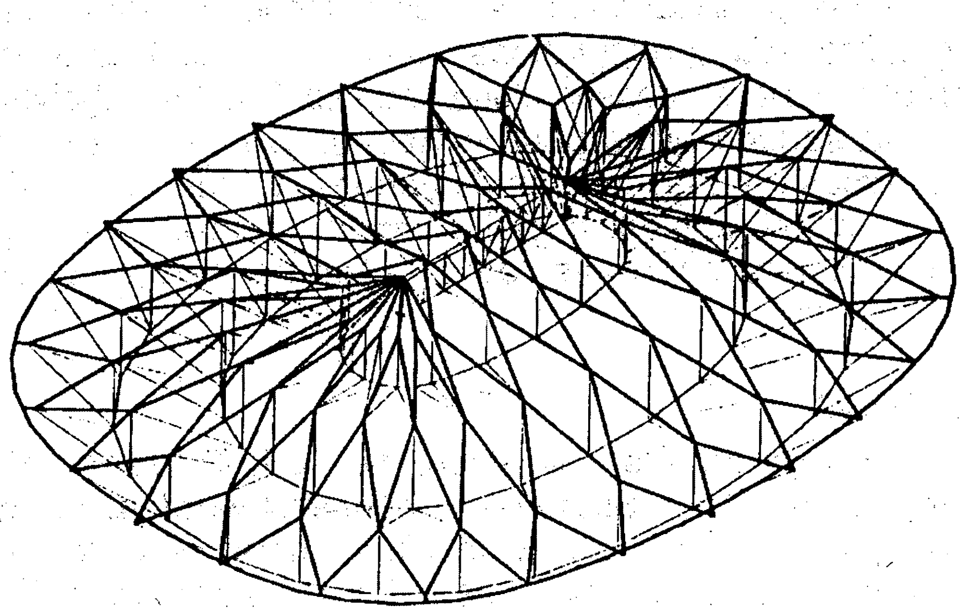


Figure 5.7: A cable network designed with tensegrity concepts.

The design scheme consists essentially of a cable dome with parallel cables on the top surface to which parallel tracks are attached. The spacing of the cables is on the order of 35', which renders the cable grid relatively invisible to a spectator looking up at the sky. The spacing is small enough, however, to permit a lightweight truss structure to be designed to ride upon it. The roof cover can be either a fabric material similar to those used in air-supported and other cable-supported roof systems or a thin, rigid metal covering. The roof panels are arranged in simple shapes that can be easily erected and maneuvered (figure 5.8).

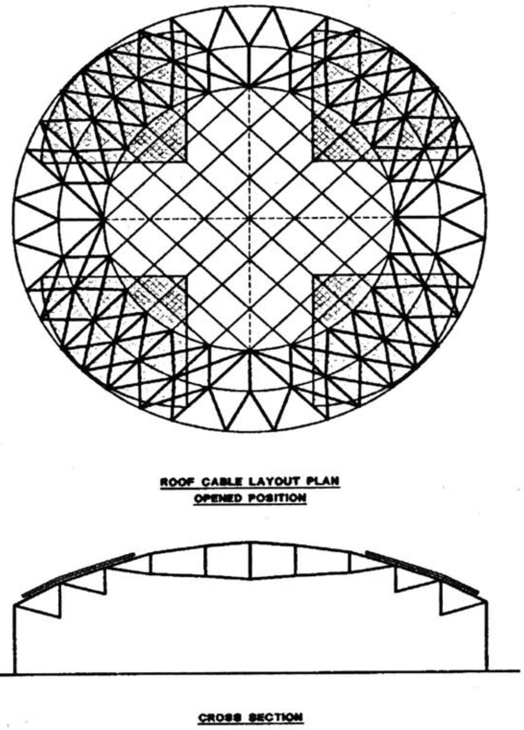


Figure 5.8: Roof cable and panel layout in opened position—plan and cross-section

Because the fabric roof sections are lightweight, the operating mechanisms that enable retraction are also small and lightweight. Two operating systems have been considered: a cable-driven system with fixed motors located on the compression ring, and a wheel-driven system with built-in electric motors directly geared to the wheels on the movable section (figure 5.9).

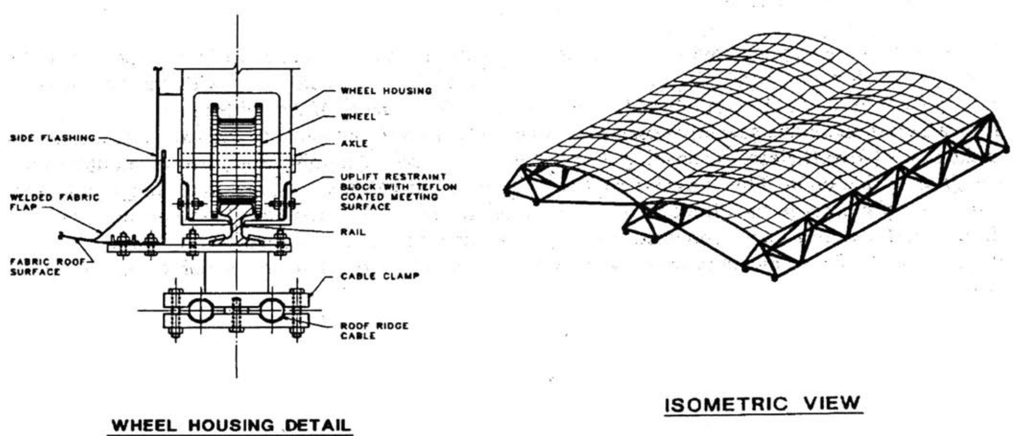


Figure 5.9: Operating mechanisms for retraction

The primary advantage of tensegrity system is that it is extremely lightweight, which reduces the cost of the roof itself and the support structures beneath. This element of the design becomes very attractive when compared to the heavy, trussed and often cantilevered retractable roofs that are currently being built. However, because the cable network remains in place at all times, the roof system is not completely retractable. As a result, unless owners and spectators can be expected to accept the visual impingement of a cable net, this system will not be as successful as other retractable roof systems.

6. Stadiums for the Future

The current trend in stadium design is either to provide traditional, open-air parks or to supply retractable roofs. Because of their versatility, retractable roofs are likely to continue to be especially popular in both cold, snowy climates and hot, humid ones. As discussed, they have already been built in Phoenix, Seattle, Houston and Milwaukee, and have been proposed in Florida and Minnesota as well. While all of these parks serve as the home of major league baseball franchises, retractable roofed stadiums have recently begun to cross over into the NFL. Massive retractable roofs have been designed for the Phoenix Cardinals and the expansion Houston Texans. Though expensive, retractable roofs are here to stay—at least for a while.

The key, however, is not to anticipate the likely trends or changes in stadium design over the next five to ten years, but rather over the 30 years or more of the design life of a stadium. Internationally renowned architect Rod Sheard of HOK+Lobb Sports Architecture in London believes that the answer—as is common in so many other engineering fields— lies in technology.

In 1998, Sheard described the evolution of sports and sporting venues as four generations. The first, the "rules" generation, allowed informal games to be organized and the rules of modern sport to be formed. This lead to a peak in spectators watching live sporting events in the 1940's and 1950's, and created the need for athletic stadiums. The second "television" generation allowed the broadcast of live sports around the world to millions of armchair viewers. This development forced stadiums to evolve in order to compete, and designers began to consider comfort and the utilization of concourses to attract audiences back to the action. We are now well into the third "entertainment" generation, where sport is big business and sporting events must compete with all other forms of leisure and amusement. In this environment, additional activities, service and spectacle are keys. Stadiums must be versatile, and able to lure a wide range of patrons to the ballpark.

The fourth generation is the "technology" generation, which refers to stadiums that provide, among others, the following elements: links to other facilities, shops, hotels and restaurants; technological infrastructure in the form of video screens and headphones in every seat; and an acoustically treated, retractable roof. Proximity to various revenue areas should boost convenience and, consequently, usage and profitability of the stadium itself. Information technology will provide the spectator with all of the advantages of a television broadcast, including statistics, instant replays and post-game interviews. Support facilities will provide amenities ranging from business centers to video arcades. Finally, according to Sheard, roof systems will continue to contribute to the overall experience of a day at the ballpark, and help characterize progress in stadium design well into the future. These attractions will be designed to encourage fans to arrive early and stay late—possibly even sleeping over in the stadium hotel.

Stadiums must have a unique individual atmosphere, offering both the thrills of live sport and a wide range of facilities that cater to all tastes and interests. The future of sport depends on providing venues that satisfy all the needs of its supporters. With the help of modern technology, engineering and design solutions can be developed with that vision in mind, in order to create a stadium that surpasses all of our expectations.

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